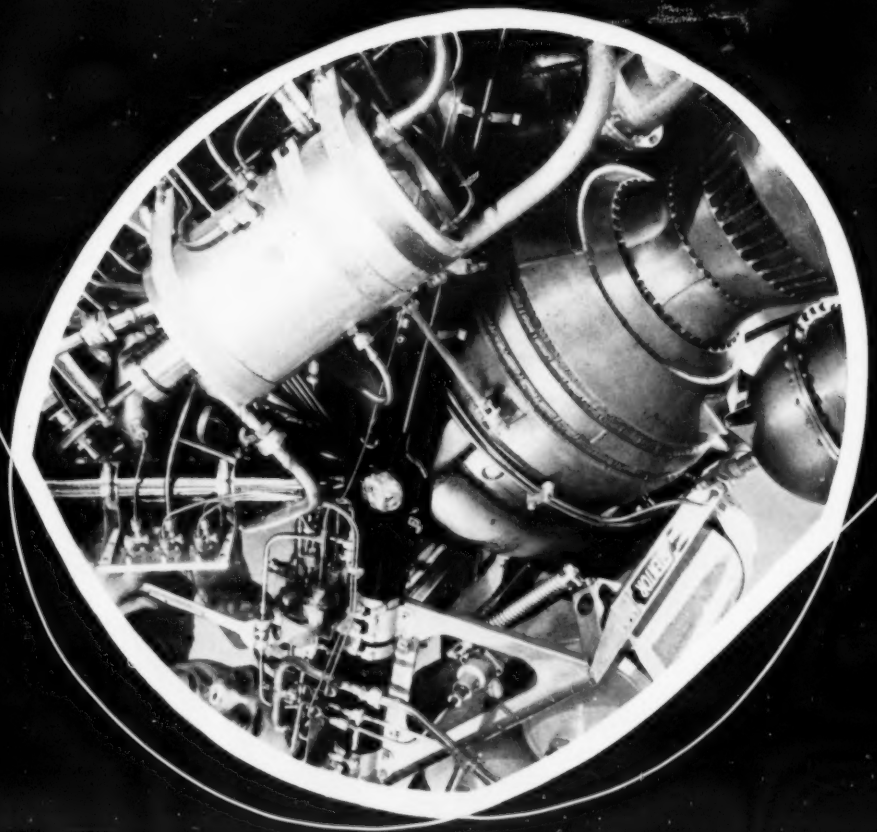

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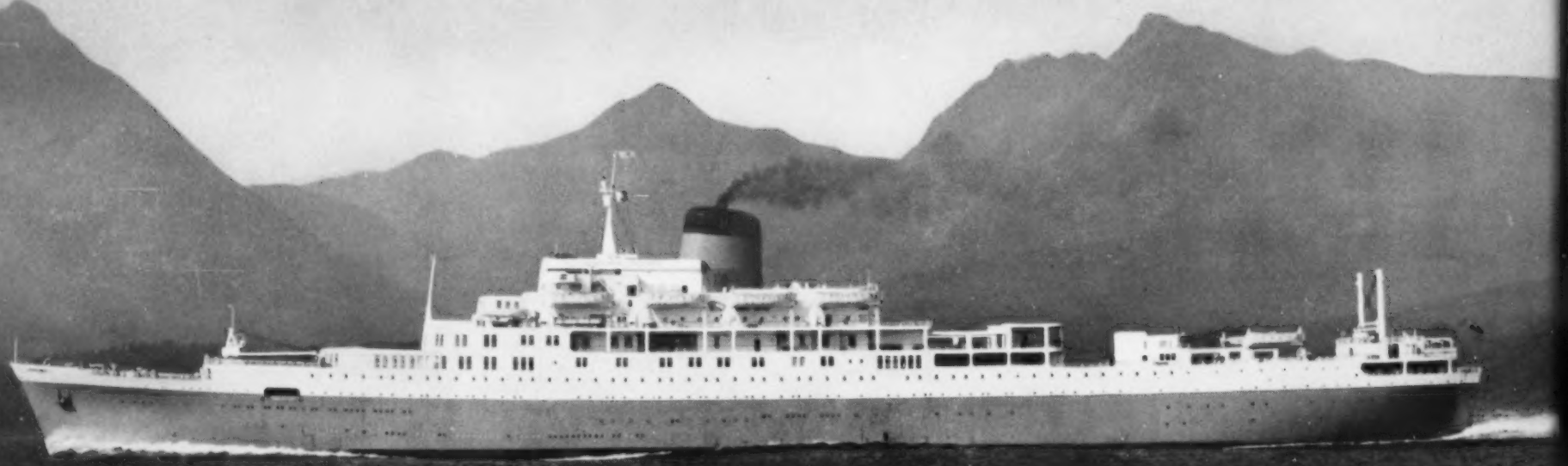

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At high temperatures, titanium rapidly absorbs embrittling elements such as hydrogen, oxygen, nitrogen and carbon. For this reason gas and metal-arc welding are not suitable, and inert-gas shielded-arc processes must be used. Most experience has so far been gained with tungsten-arc welding.

Provided that all heated surfaces are adequately shielded, titanium is one of the easiest metals to join. Unfilled welds are preferable to filled welds as it is easier to keep them free from contamination; the tip of the filler wire, if used, should always be maintained within the argon shield and the wire should be fed into the weld pool smoothly.

To avoid contamination and subsequent embrittlement, filler materials must be free from surface oxide and grease. Filler wire of commercial purity titanium, and of I.C.I. Titanium 317 and 230 alloy, is manufactured to high standards of quality by I.C.I. Metals Division. As it is always supplied descaled and pickled, there is no risk of contamination by the filler material provided that it is kept clean.

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I.C.I. Titanium 115 120 130	0.036 in. to ¼ in. diameter, in straight lengths or in 5-20 lb. coils, depending on diameter. (I.C.I. Titanium 130 also on spools for I.G.S.M.A. welding)	Welding Titanium	Argon arc	None	1660
I.C.I. Titanium 317 (5% aluminium, 2½% tin)	⅛ in. to ½ in. diameter or 0.080 in., 0.064 in. or 0.048 in., in straight lengths; or in coils, 3 lb. maximum weight, down to 0.036 in.	Welding I.C.I. Titanium 317	Argon arc	None	1590
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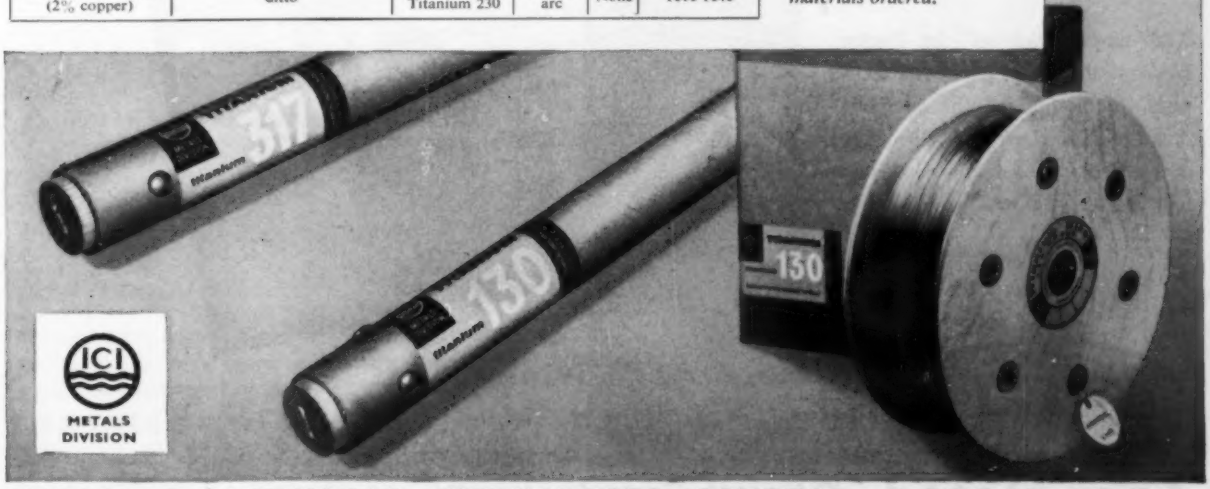

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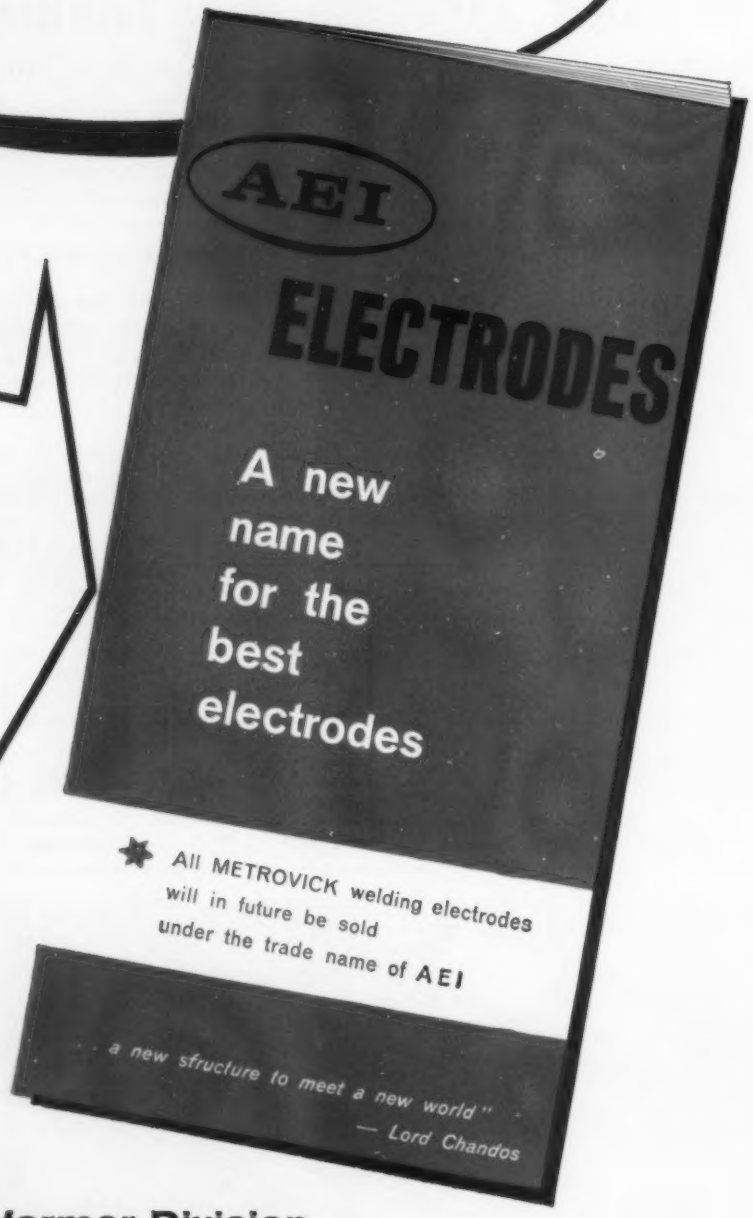
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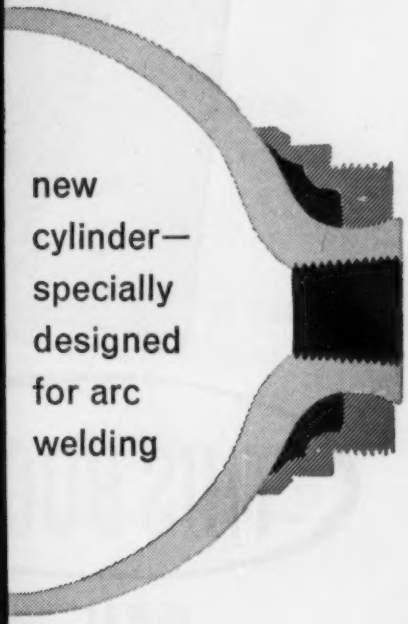

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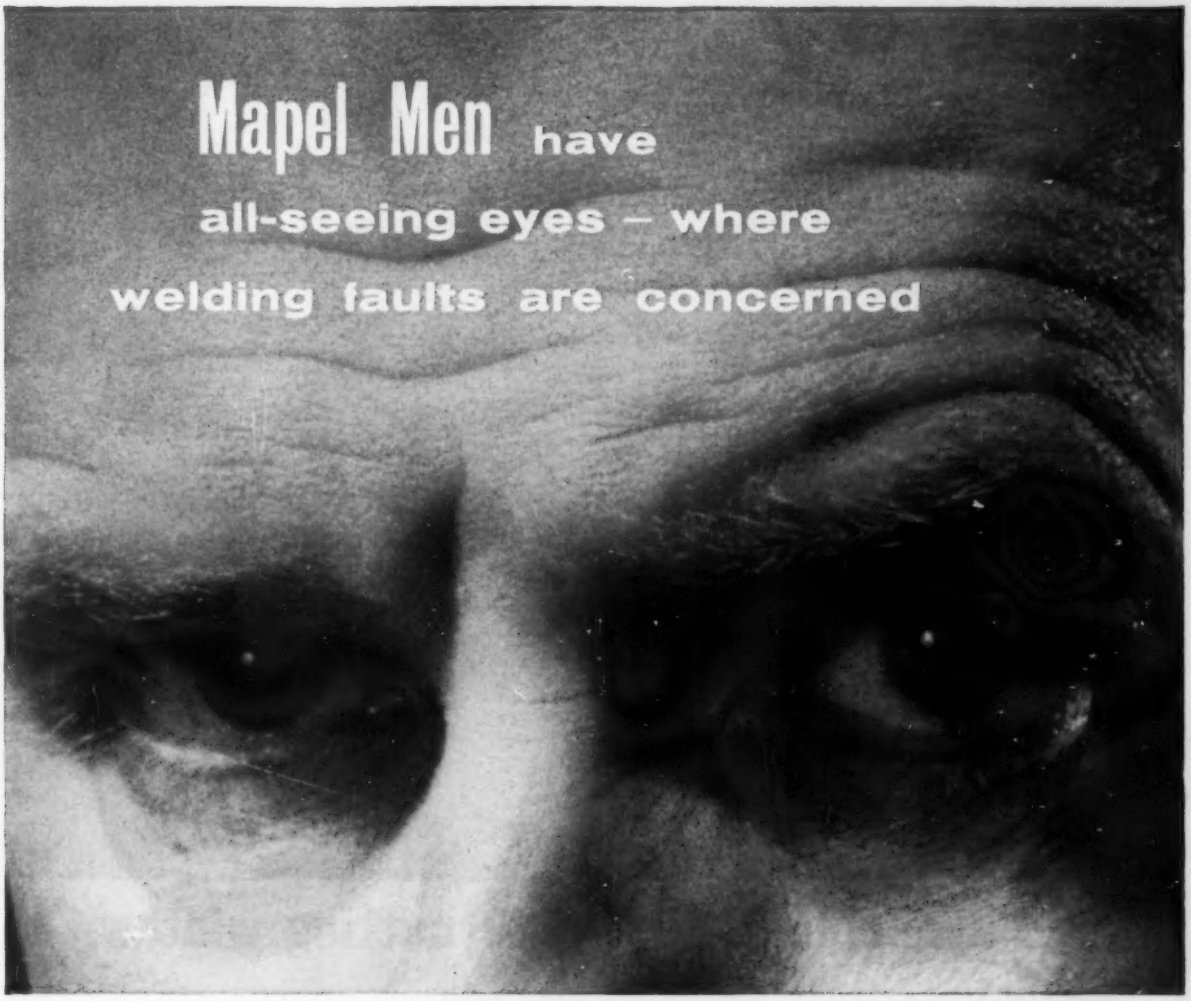

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Seam aluminium up to	.010″	Spot S.A.P. up to	.036″
Spot brass up to	.004″	Spot Beryllium up to	.080″
Spot magnesium up to	.064″	Spot Zirconium up to	.048″

THE QUALITY OF WELD has significant advantages—FOR INSTANCE IN REDUCED DEFORMATION—over welds in comparable thicknesses by other methods. The examples give an indication of the range within which advantageous results are obtained.

Spot aluminium up to .048″
Spot stainless steel up to .064″
Seam stainless steel up to .020″
Spot Titanium, Nimonic and Monel up to .036″

COMBINATIONS OF DISSIMILAR METALS can be satisfactorily welded. Examples are:—

Spot and seam copper up to .005″ to aluminium .005″
Spot .005″ copper to .014″ stainless steel
Spot brass .004″ to stainless steel .007″

METALS OF DISSIMILAR THICKNESSES can be satisfactorily welded, for instance:—

.004″ stainless steel can be seam welded to .75″ stainless steel.

THE STRENGTH OF WELD depends on the metal and type of joint. In the metals and thicknesses quoted above weld strengths of practical engineering value are consistently obtainable. Development work is extending the range of effective application. Examples of weld strengths in particular metals are:—

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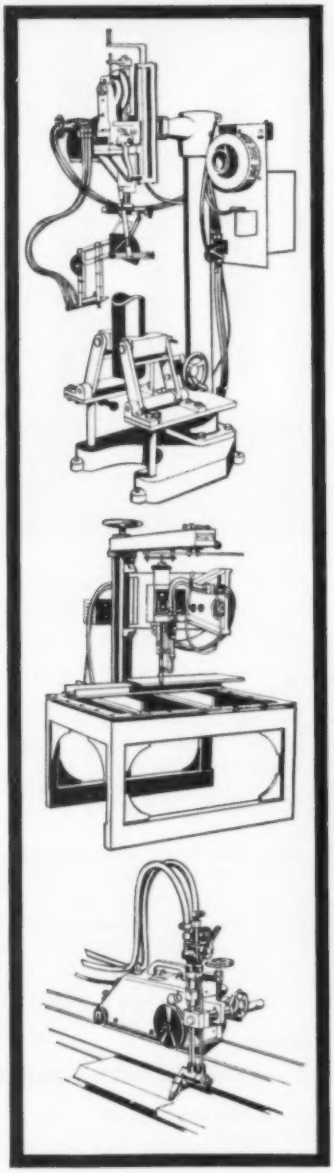

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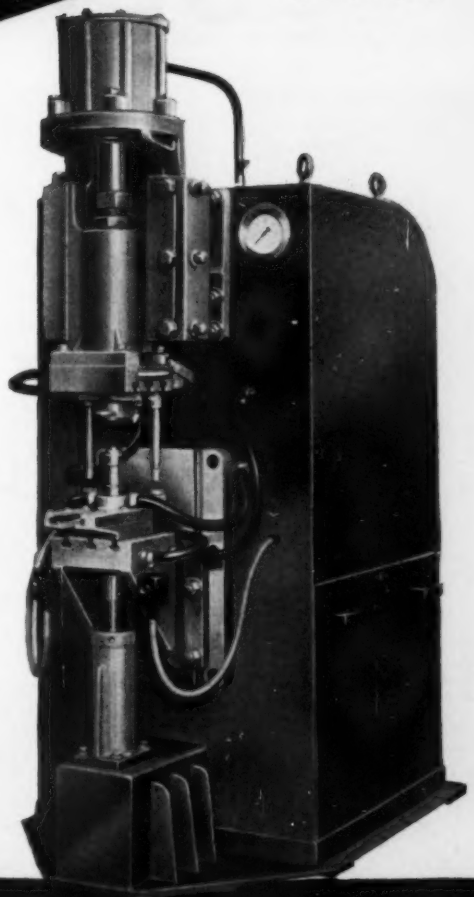

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Incorporating the *TRANSACTIONS* of the Institute and *WELDING RESEARCH*

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AUTUMN MEETING 1960

Distribution of Phosphorus and Sulphur in Fully Austenitic Stainless Steel Welds

By S. M. Makin, B.SC.,PH.D., *C. B. Alcock*, B.SC.,PH.D., *D. R. Arkell*, L.I.M, *and P. C. L. Pfeil*, B.SC.,PH.D.

Small additions of radioactive sulphur and phosphorus were made to a 24% Cr–21% Ni stainless steel, which was fabricated into thin sheet. Welds were examined by autoradiography and metallography.

The concentration of phosphorus in the middle of the weld zone was measurably greater than in the original sheet. This concentration resulted from depletion of the first metal to solidify along the sides of the weld. Phosphorus was also found to concentrate in the interdendritic regions of a casting of a basically similar steel. Phosphorus therefore is important in the hot-cracking of fully austenitic stainless steel welds.

Sulphur, however, was not concentrated preferentially in the weld metal and therefore it was concluded that sulphur is not important in the formation of cracks observed in these welds.

UNTIL quite recently the search for satisfactory cladding materials for fuel elements in nuclear reactors has been concentrated on the metallic elements and alloys having low capture cross sections for thermal neutrons. Now that higher operating temperatures are essential, alloy steels, especially those having a high oxidation resistance, are being considered for this function, despite their relatively high neutron absorption.

The cladding of a fuel element is made from light-gauge tube, and one might reasonably expect that welding problems would not be serious. However, the service conditions of thermal and stress cycling means that the presence of cavities or fine cracks in the weld metal could limit the fuel element life and add to the costs of power production.

In a recent review of the literature on the cracking of welds in Cr-Ni austenitic steels Borland and Younger[1] indicated, *inter alia*, that sulphur and phosphorus may be important in the formation of cracks. The precise mechanism, however, is not clear. One approach to this problem is to investigate any change in the distribution of these elements in welded material compared with fabricated material.

Since sulphur and phosphorus both have β-emitting radio-isotopes it was decided to study their distribution in welds in a stainless steel by autoradiography. The experimental procedure was to incorporate the radio-active element into a steel billet, which was then arc-melted and rolled; the resultant sheet was then used for making butt welds and weld runs. The welds were mounted and polished in the conventional metallographic manner, and autoradiographs showing the distribution of the radio element were obtained. Most

Manuscript received 6th July, 1960.

Dr. Pfeil and Mr. Arkell are in the Metallurgy Division of the Atomic Energy Research Establishment, Harwell. Dr. Makin was formerly with the U.K.A.E.A. Wantage Radiation Laboratory. Dr. Alcock is a Lecturer in Metallurgy at the Imperial College of Science and Technology.

of the work has been on 24% Cr–21% Ni alloys, but a 20% Cr–20% Ni composition, which is less prone to sigma embrittlement, has also been used.

Experiments with Radioactive Sulphur (S^{35})

Preparation of the radioactive alloy

About 30 mg of radiosulphur of specific activity about 3 mc/g were mixed with 300 mg of pure iron powder in a Pyrex ampoule. The ampoule was evacuated and then sealed off. The mixed powder was gently heated to initiate reaction between the elements, and when this ceased the ampoule was placed in a muffle furnace for about 8 hr at 400°C. to ensure completion of the reaction. A 200 gm cylinder of 24% Cr–21% Ni stainless steel was prepared with a ¼ in. dia. hole along its axis for half its length. After removal from the ampoule, the powder was poured into the hole, which was then closed with a plug made from the same steel.

The sample was melted six times in an argonarc furnace with a water-cooled copper hearth, to ensure homogeneity of the alloy. The resulting 'pancake' was hot rolled, using a constant rolling direction, until a sheet about 0·13 cm thick was obtained. This was given the standard annealing treatment for the parent material, *i.e.*, 30 min., 1050°C., quench.

The composition of the steel was then, nominally, Cr 23·7%, Ni 21%, Si 1·37% Mn 0·81%, P 0·015%, C 0·08% with the balance iron. The sulphur determined by analysis was 0·035%.

Samples of the sheet were then submitted to argonarc welding to produce (*a*) a simple melt run; (*b*) an autogenous butt weld; and (*c*) a melt run terminating halfway across the sheet. All of these were made under a clamping constraint parallel to the direction of welding. A melt run was also made without this constraint. All samples showed considerable cracking.

Pieces containing the welded areas were cut from the surrounding material, mounted in Bakelite and polished metallographically. The final thickness of the weld specimens was about 0·1 cm, the unpolished faces still having the normal irregularities of a weld surface.

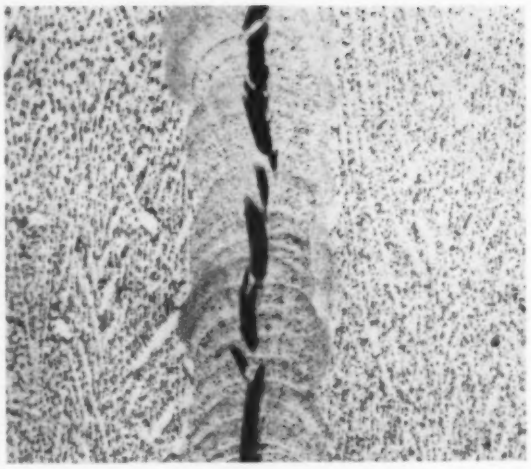
Autoradiography

The energy spectrum of the β rays from the sulphur 35 isotope has a maximum[2] at 0·167 MeV, which corresponds to a range in steel of approximately 0·005 cm. Thus, the resolution of the sulphur autoradiographs was not significantly affected by the direct use of the relatively thick welded specimens.

A fairly high speed emulsion X-ray film was used for autoradiographs taken during the preliminary investigation, and required exposures of several days. Better resolution was obtained by using a slower, finer grained film but no new features were revealed.

Figure 1 is a typical autoradiograph showing the details of the S^{35} distribution in a weld.

The sulphur distribution followed the visual appearance of an etched microstructure of a weld. The dark regions down the centre of the autoradiograph, corresponding to the centre of the weld, are the cracks. These possibly show up so strongly because of multiple scattering of the β rays down the inner surfaces of the cracks and into the film. There appears to be no evidence of concentration of sulphur in the weld material as compared with the unwelded matrix. The differences in scale and alignment of the S^{35} rich regions between the 'over-lapping plates' and the matrix material suggests that the former covers that part of the sample that was molten during welding.



1—Autoradiograph of weld containing 0·035% S, showing distribution of S^{35} ×6·4

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The procedure for making the radiophosphorus-bearing alloys was the same in the first instance as that for the sulphur alloys, elementary radiophosphorus of a specific activity of 1·04 mc/g being used. The final phosphorus content of the alloy was found by chemical analysis to be 0·033 wt %.

This alloy was more brittle than the sulphur alloy, and it was difficult to obtain samples without the cracks in the welds spreading right across the specimen. Thus, in only a few instances could samples be prepared for autoradiography with both sides of the weld still in contact.

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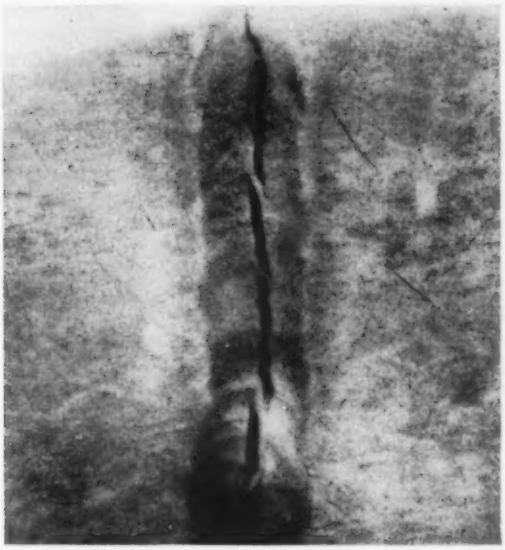
Another alloy was made from relatively pure materials by melting together iron, chromium, and nickel, all of approximately 99·95% purity, to make a 20% Cr–20% Ni stainless steel. To 150 g of this melt 6·5 mg of radiophosphorus of a higher specific activity of 770 mc/g were added. This material was



2—Autoradiograph of weld containing 0·033% S, showing distribution of P^{32} ×6·4

then rolled into sheet 0·09 cm thick and a melt run was made. A piece including the weld was polished down on both sides to give a final parallel-sided specimen approx. 0·008 cm thick. An autoradiograph of this thin section (Fig. 3) showed again the concentration of phosphorus in the weld. This low-phosphorus steel was etched electrolytically in a solution of 20% H_2SO_4 in water at 2 V for 2 min, and the micrograph shown in Fig. 4 was obtained. The central area shows a fine etched structure which corresponds to the high-phosphorus area in the autoradiograph. The areas in the autoradiograph which are depleted in phosphorus can be related to the first material to solidify, *i.e.*, the material immediately beside the fine etched area.

Densitometry

To make a materials balance between the enriched and depleted zones of the welded sample, measurements were made of the optical density of the autoradiograph shown in Fig. 3. The result, shown in Fig. 5, indicates that approximately the amount of material removed from the depleted zone can be accounted for in the enriched zone assuming that the section studied is representative.

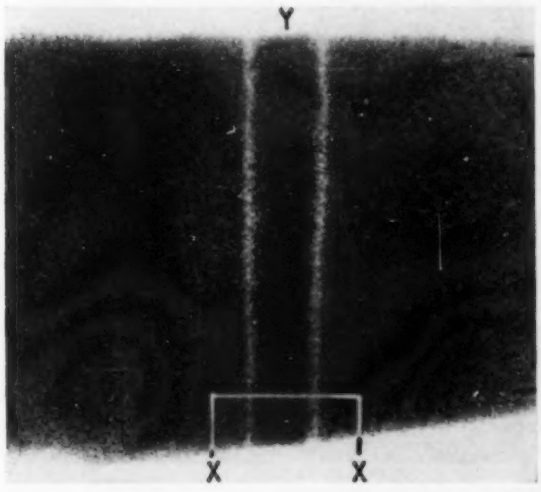
Activation analysis

The phosphorus content of the welded zone of the 0·033% phosphorus 24/21 steel was compared with that of the unwelded matrix by neutron activation analysis. No absolute determination was made but an enrichment of three times was indicated in the welded zone; this result is not necessarily typical, for the conditions of sampling were not rigorously controlled.

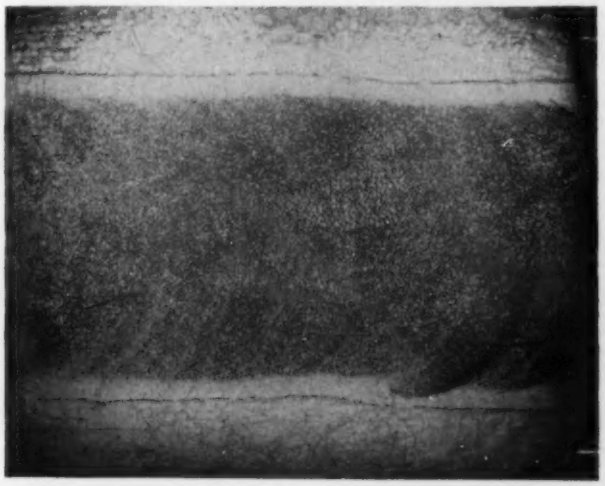
Metallography

The experiments described have shown clearly that, on the macroscale, phosphorus is enriched in the weld material. Experiments were then made to find out if phosphorus was redistributed on the microscale in stainless steel alloys.

Some evidence for the presence of a light grey phase at isolated places along the cracks in the 24% Cr–21% Ni alloy containing 0·033% phosphorus was found. This phase was not found in that part of the steel away from the weld. To obtain further evidence it was considered necessary to increase the concentration of phosphorus above the normal specification, and an alloy containing 0·24% phosphorus in the same composition was made and argonarc melted. A thin polished section of this casting, 0·008 cm thick, was made and both micrographs and autoradiographs were made from the section. These are shown in Figs. 6 and 7 respectively. Columnar dendrites can be seen at the bottom and an equiaxed region at the top. It is clear from comparison of the two figures that on the microscale a concentration of phosphorus occurs



3—Autoradiograph of thin section containing 0·004% P, showing distribution of P^{32} along melt run ×5



4—Micrograph at Y in Fig. 3, showing difference in structure between first metal to solidify and bulk of molten zone (etched 20% H_2SO_4 for 2 min) ×27·4

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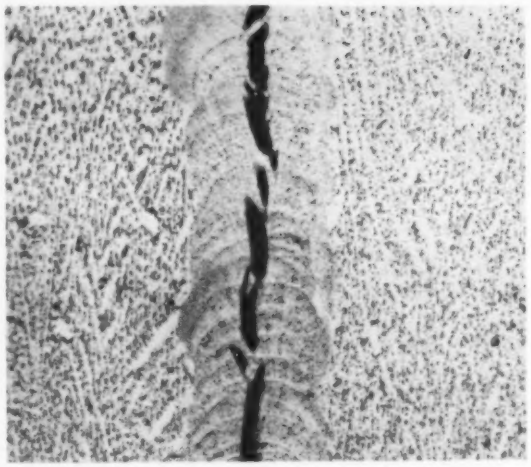

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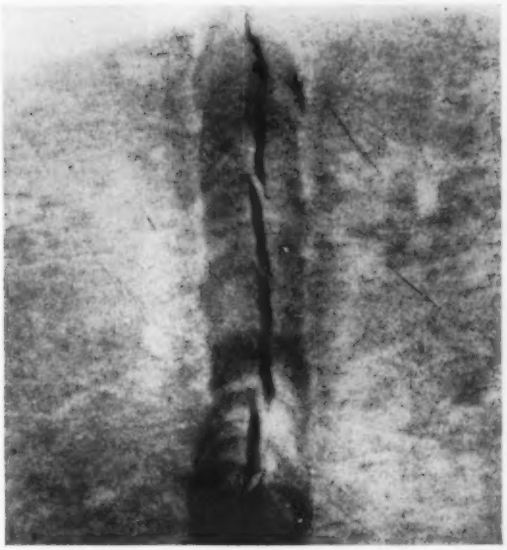

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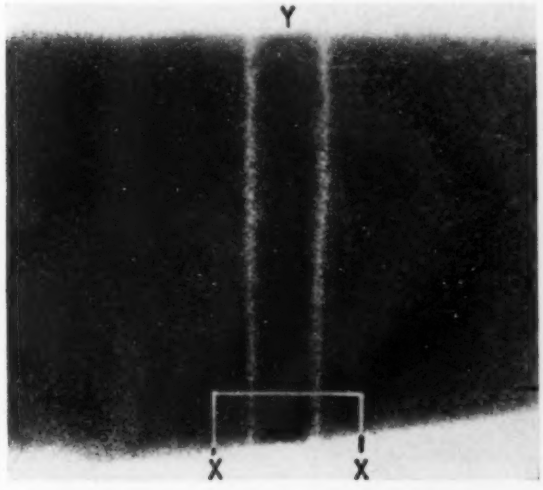

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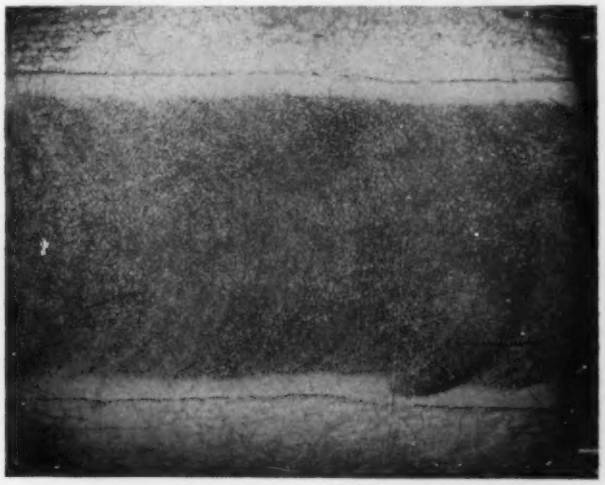


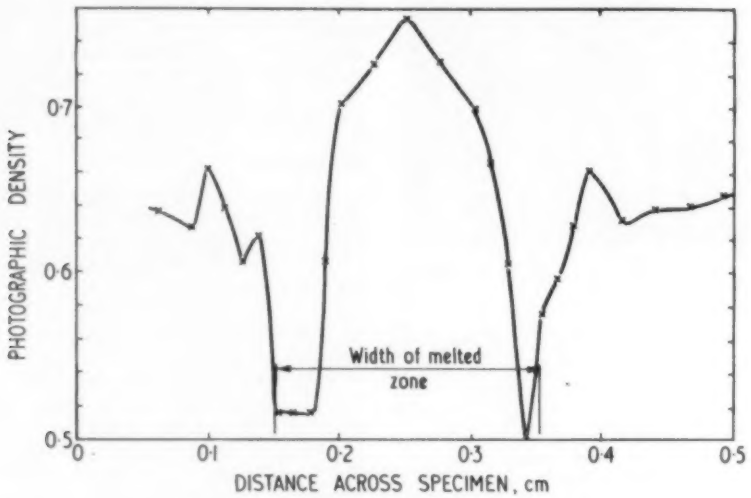
4—Micrograph at Y in Fig. 3, showing difference in structure between first metal to solidify and bulk of molten zone (etched 20% H_2SO_4 for 2 min) ×27·4

in the interdendritic regions. This has previously been found in carbon and low-alloy steels.[5]

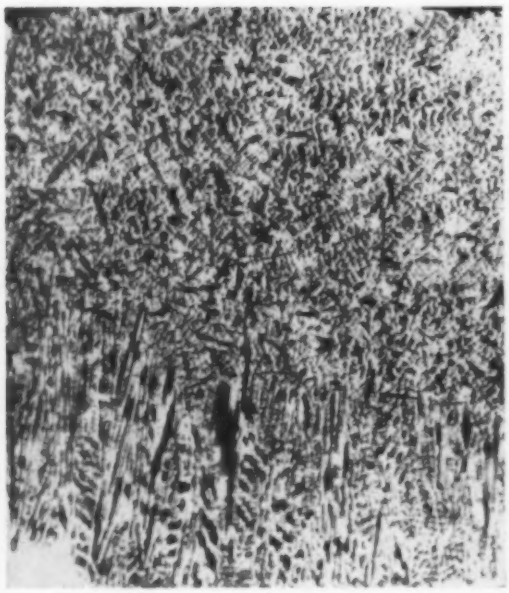
Micrographs from a lightly etched section of this material were taken at a higher magnification (Figs. 8 and 9). Figure 9 strongly suggests that two constituents are present in the interdendritic material. One of these constituents, the light grey phase, resembles, in appearance and response to polarized light, the phase present in trace amount near the weld in the 0·033% phosphorus steel.

Discussion

The present work shows that when a weld in a fully austenitic Cr/Ni stainless steel solidifies, the first metal to do so is poor in phosphorus. The remaining liquid is therefore enriched in phosphorus. Furthermore, phosphorus can be concentrated between dendrites and give low freezing point eutectics. The presence of such a constituent is believed to be one of the conditions necessary for weld cracking.[1]



5—Micro-photometer scan across X–X of Fig. 3



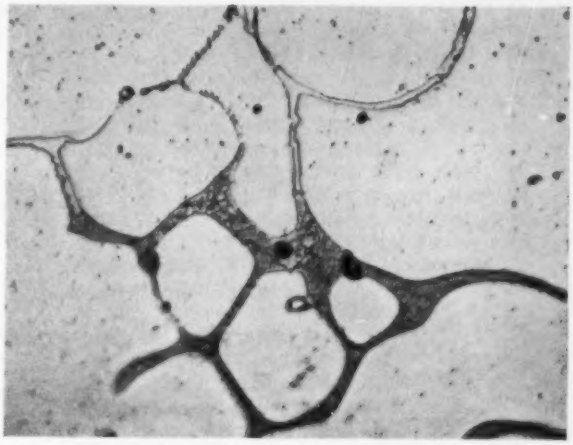
6—Micrograph of casting containing 0·24% P, showing columnar crystals and small equi-axed dendrites (oblique illumination: Etched 20% H_2SO_4 for 30 sec) ×14

7—Autoradiograph of same area as Fig. 6, showing interdendritic segregation of P^{32} ×14

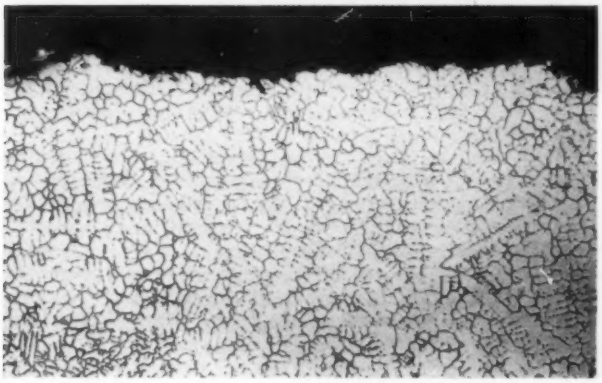
In most of the work an unstabilized commercial-type alloy was used, and the minor constituents did not prevent segregation of the phosphorus. The work gives no evidence regarding the possibility of the segregation of these constituents themselves nor whether they affected the amount of cracking found.

Since iron, chromium, manganese, and nickel all form eutectics with phosphides of the form M_3P, a eutectic between a γ (Fe, Ni, Cr, Mn) solid solution and a phosphide of the type $(Cr, Mn, Ni, Fe)_3P$ of comparatively low melting point may reasonably be expected theoretically.

However, the absence of cracks in the weld runs of the steel with nominally 0·005% phosphorus cannot be cited as proof that reducing the phosphorus content necessarily improves weldability, because this experiment was different in several other respects. The sheet thickness was considerably less; the steel also had a very low carbon content, which has been emphasized as a factor affecting hot cracking by Russian workers, *e.g.*, Lashgo and Lashgo-Avakyan.[3]



9—Micrograph of casting containing 0·24% P, showing interdendritic constituents (etched 20% H_2SO_4 for 10 sec) ×1500



8—Micrograph of casting containing 0·24% P, showing large amount of interdendritic constituents (etched 20% H_2SO_4 for 10 sec) ×50

On the other hand, the present work on a steel containing 0·035% sulphur and 0·81% manganese gave no indication that the sulphur content was responsible for the hot cracking found.

Since sulphur contents of less than 0·035% are normal and since a manganese content of this order can be tolerated in most nuclear applications of stainless steel, work directed towards the behaviour of sulphur was discontinued.

Autoradiography using tracers appears to be a useful technique for obtaining evidence on the movement of elements during welding. If the range of the radiation emitted by the radioactive species is large, and good resolution is required, thin sections must be used. Sections of one or two hundredths of a centimetre can be made by standard techniques,[3] and by applying the thinning techniques associated with transmission electron microscopy it may be possible to make thinner sections in the future. Possible errors also arise if there is lack of homogeneity in the distribution of the radioactive tracer before welding; and it is important to take this into account. Ambiguities of interpretation also arise if the material contains physical or chemical defects, *e.g.*, blowholes, cavities, large inclusions, or segregates.

Acknowledgments

The authors wish to acknowledge workers in the Fabrication Group of Metallurgy Division for the special care taken in the incorporation of tracers into steel melts, in the rolling, and in the welding.

Mr. L. B. Griffiths kindly performed the iron-phosphorus reaction for us in one case, and the high activity preparation was done at the Radiochemical Centre, Amersham.

We would also like to thank Dr. D. Gibbons for the neutron activation analysis, and Miss P. M. Stopana for assistance in the preparation and autoradiography of the samples.

REFERENCES

1. J. C. Borland and R. N. Younger: *Brit. Welding J.*, 1960, vol. 7, p. 22.
2. C. J. Smithells: "Metals Reference Book", 1955, vol. 1, p. 52 (Butterworths).
3. S. M. Makin: I.A.E.A. Conference on the use of radioisotopes in the physical sciences and industry, Copenhagen, Sept. 6–17 1960.
4. N. F. Lashgo and S. V. Lashgo-Avakyan: *Avto Svarka*, 1958, vol. 9, p. 99 (B.W.R.A. translation 15/59).
5. A. Kohn: Radioisotope Conference II. 1954, p. 68 (Butterworths).

AUTUMN MEETING 1960

Whither Electrode Design?

By I. C. Fitch, A.M.I.MECH.E., M.INST.W.

The paper considers the reactions in the welding arc and some of the problems of measuring them. Progress in the design of alloy steel electrodes is considered. The problems of moisture pick-up by low hydrogen electrode coatings and future developments of electrodes with coatings loaded with alloys and iron powder are discussed.

ELECTRODE design has been greatly influenced by progress in manufacturing technique. Most early electrode coatings were applied by dipping and the popular ones were no doubt those least affected by the difficulty of controlling the diameter and concentricity of the coating. Additions of alloys to such electrodes tended to settle from the dipping slurry and made control of composition most difficult.

As this method of manufacture was superseded by wrapped and extruded coatings control of composition and dimensions improved and designers were freed from the shackles of the dipping process.

Experience in the operation of equipment for making fully extruded electrodes has led to a better understanding and control of the variables involved, so that production of electrodes with heavy coatings loaded with alloys and iron powder has become a practical proposition.

As a result of these changes, old problems sometimes take on new significance, and this paper re-examines some of them to stimulate new thought.

Steelmaking Reactions

The reactions in the welding arc are similar to those in steelmaking, but by comparison with steelmaking the volume of metal reacting at any instant is small and the slag to metal ratio is high. The reaction time is very short but the temperature is high, and it is probable that the reactions attain a state akin to equilibrium. The state attained produces weld metal that is remarkably consistent in its properties when it is realized how different are the temperatures of each part of the weld pool and that each part will tend towards a different equilibrium composition.

Such is the degree of stirring, however, and the uniformity of the pattern of change of temperature in the pool, that each part receives very similar treatment.

In steelmaking it is possible to add the refining materials in sequence or even to change the slag completely. This is a degree of freedom not possible in welding, so the materials of the core and coating must be relatively pure and the reactions limited mainly to de-oxidation and the addition of alloys.

Functions of Welding Slags

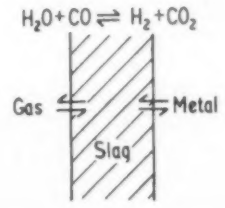
Welding slags are required to perform duties not expected of steelmaking slags since they must have the right combination of surface tension and viscosity to permit proper control of the weld metal and must include constituents contributing to the stability of the arc.

Electrode coatings also contain materials that generate gases to assist the slag in protecting the metal from contamination by nitrogen from the air.

The gas shield commonly contains a mixture of H_2, H_2O, CO, and CO_2, the constituents of which react with the slag and with one another to reach an equilibrium whose balance is dependent on temperature[1] (Fig. 1).

The reactions between gas and slag and slag and metal cause a lively exchange of carbon, oxygen, and hydrogen, the net result of which is for carbon to be lost and for oxygen and hydrogen to go into the metal.

Not only is there an equilibrium between the gases in the gas shield but within the metal a balance is struck between the carbon and oxygen such that as one increases the other decreases in proportion. When the metal solidifies, sufficient manganese must be present to 'lock up' the oxygen in solution and to combine with sulphur to prevent the formation of iron-sulphide films at the grain boundaries.



1—*Reactions in the arc*

It is interesting to consider the effect of adding water vapour to such a system.[2] The vapour pressure of the

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Table I

Vapour pressure of gas shield constituents

Equation A: $H_2O+CO = H_2+CO_2$

B: $pH_2O+pCO+pH_2+pCO_2 = 1$

C: $\frac{pCO_2 \times pH_2}{pCO \times pH_2O} = K$ ($K \approx 0{\cdot}25$)

	Case 1			Case 2		
	Steps	*K*	*Total*	*Steps*	*K*	*Total*
1.	$\frac{0{\cdot}16 \times 0{\cdot}1}{0{\cdot}64 \times 0{\cdot}1}$	0·25	1·0	$\frac{0{\cdot}1 \times 0{\cdot}16}{0{\cdot}1 \times 0{\cdot}64}$	0·25	1·0
	Add 0·1 H_2O			Add 0·1 H_2O		
2.	$\frac{0{\cdot}16 \times 0{\cdot}1}{0{\cdot}64 \times 0{\cdot}2}$	0·125	1·1	$\frac{0{\cdot}1 \times 0{\cdot}16}{0{\cdot}1 \times 0{\cdot}74}$	0·216	1·1
	Correct total					
3.	$\frac{0{\cdot}145 \times 0{\cdot}091}{0{\cdot}582 \times 0{\cdot}182}$	0·125	1·0	$\frac{0{\cdot}091 \times 0{\cdot}145}{0{\cdot}091 \times 0{\cdot}673}$	0·216	1·0
	Correct *K* by adding to items in top line and subtracting equally from bottom line					
4.	$\frac{0{\cdot}175 \times 0{\cdot}121}{0{\cdot}552 \times 0{\cdot}152}$	0·25	1·0	$\frac{0{\cdot}096 \times 0{\cdot}150}{0{\cdot}086 \times 0{\cdot}668}$	0·25	1·0
	pH_2 increases 0·1 to 0·121			decreases 0·16 to 0·15		

principal constituents shown in equation *A* of Table I must total one atmosphere, as shown in equation *B*, and the proportions adjust themselves so that equation *C* is satisfied, the value of *K* being approximately 0·25 at the temperature of the arc.

If two cases are considered, the first such as would occur in the arc of a low-hydrogen electrode and the second appropriate to a class 2xx electrode, it is possible to demonstrate that adding water vapour in the first case increases the pressure of hydrogen in the arc and in the second, contrary to expectations, decreases it.

Step 1 assumes reasonable values for the partial pressures in equation *C*, such that their total is 1·0 and *K* is 0·25. Step 2 assumes that 0·1 of water vapour is added to the system, but since neither equation *B* nor *C* is then satisfied, step 3 scales down all the values to satisfy equation *B*, and step 4 adjusts the values in the top line by adding to each item the same amount as is subtracted from the bottom items until equation *C* is once again satisfied.

That this procedure is valid can be seen if in equation *A* one molecule of H_2O is dissociated into H_2 and O.

The right hand side then gains one molecule of H_2 and the left loses one of H_2O.

The oxygen combines with one molecule of CO to produce one more molecule of CO_2, so once again the left hand side loses one molecule of CO and the right gains one of CO_2.

This explains why drying rutile-type electrodes sometimes increases the hydrogen content of the weld metal they produce.

Slag Viscosity and Surface Tension

The viscosity and surface tension of the slag and weld metal are dependent on their temperatures. Since the temperature ranges from perhaps 3000°C. to less than the melting point of the metal over a distance that may be less than $\frac{1}{2}$ in., it is easy to understand that the conditions near the arc are very complex, and why no record exists of a successful attempt to measure these variables under practical conditions.

Gledhill measured the viscosity/temperature relationship for 75 slags in 1950 under the guidance of the FM.5 Committee of B.W.R.A.[3] This work showed that welding slags were generally less viscous than steelmaking slags and demonstrated the effect on viscosity of variations in the composition of these slags. No clearly defined correlation was apparent however between the viscosity/temperature characteristics of these slags and the welding characteristics associated with them. Results of similar tests according to Hartmann are quoted by Séférian.[4]

Several factors come to mind that could not be satisfactorily reproduced in these tests and which could have had an important effect. Dissolved gases have been shown to modify the viscosity of glasses, and since slags are glass-like in nature, it is probable that the need for protecting the iron crucible from oxidation by working in a nitrogen atmosphere prevented any attempt to employ the atmosphere that would normally be in contact with the slag. An iron crucible was chosen because the slags were likely to react with any other crucible into which they were placed and iron was the material with which they would normally be in contact.

In the course of the experiments it became clear that ilmenite crystallized from some rutile-bearing slags as they cooled and had an important effect on the results. In practice, the pasty condition of such slags as they cool must change their fluidity to a marked degree and, since the crystals are likely to be oriented, the practical properties of the slag are unlikely to agree with those measured in the viscometer.

In the face of these difficulties it is not surprising that trial and error methods continue to be used to arrive at a suitable slag performance and that individual judgment plays a large part in the determination of the performance of new electrodes.

There is little doubt that a solution of these difficulties would lead to rapid progress in electrode design. Present methods are extremely uneconomical in both time and material and often it is impossible to know whether real progress is being made or not.

Alloy Steel Electrodes

Substantial progress has been made in the technique of designing alloy steel electrodes. This has been largely due to the finer control of coating size and density attained by modern manufacturing methods, which make it feasible to control the weld composition within limits that are closer than is usual in steelmaking. To achieve this result all or part of the alloys are introduced by incorporating them in the electrode coating.

The success with which alloys may be added is dependent on the type of coating and the degree to which the alloy combines with the slag or with oxygen, or is volatilized by the heat of the arc. The recovery of those elements that are readily oxidized or volatilized is affected by the arc length to a noticeable degree. Basic coatings are generally the most satisfactory for producing alloy deposits and Table II gives some idea of the recovery that may be expected of the more common elements.[5]

Table II

Transfer efficiencies

C,	35– 45%	Nb,	40–50%
Si,	10–100%	W,	70–85%
Mn,	20– 70%	V,	40–60%
Fe,	85– 95%	Ti,	very low
Ni,	50– 95%	Zr,	very low
Cr,	45– 85%	Al,	very low
Mo,	90–100%	Mg,	very low

Accurate values cannot be given because the recovery of an element may be influenced by the amount present or by the presence of other elements. Unless account is taken of the loss of iron in the arc it is possible to arrive at the conclusion that the recovery of some elements is greater than 100%; but this can be true of silicon, which may be reduced from the slag.

Low-Hydrogen Electrodes

The technical advantages of a low hydrogen content in alloy steel weld metal and even in mild steel under conditions of heavy restraint are now well known.[6,7]

The practical difficulties entailed in making sure that these electrodes are sufficiently dry when they are used have proved to be an obstacle to their wider application, and it is felt that discussion of this problem will be helpful.

It is important to understand that low hydrogen does not mean hydrogen-free, and that however much an electrode is dried some hydrogen will remain combined with necessary coating constituents.

No satisfactory coating binder has been found that is free from combined water. Sodium or potassium silicates are normally employed for this purpose since they can be readily mixed with the powders forming the coating, and after baking at temperatures up to approximately 450°C. behave very much like glass.

The employment of glasses with low softening temperatures has been proposed as an alternative, but oxidation or decomposition of some of the coating constituents is likely to occur at temperatures greater than 450°C. It is difficult to obtain a satisfactory glass bond at this temperature, and unfortunately glasses with a low softening temperature tend to adsorb or absorb moisture rather easily.

How Much Moisture can be Tolerated?

It is generally true that the higher the hardness of the weld or parent metal the lower must be the hydrogen content if freedom from cracking is to be achieved. The tendency to crack is aggravated by restraint, and some steel compositions are more prone to crack than others of equal hardening potential. The standard of dryness that is acceptable for each class of work, electrode, and type of steel is a matter on which it is difficult to make an authoritative statement since there are too many variables to be considered, and it is not surprising that electrode makers express divergent views on this matter.

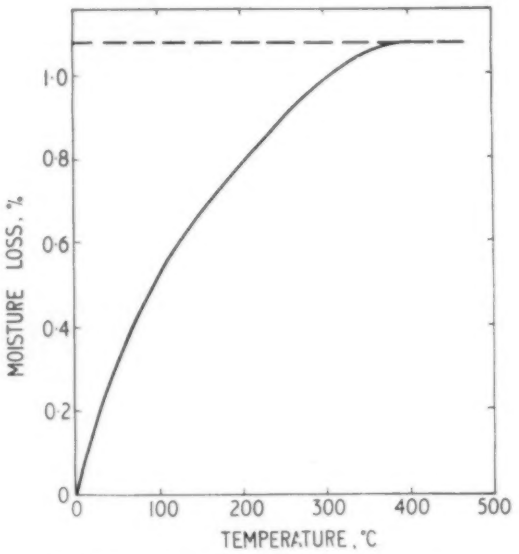
The mechanism of drying of electrodes and regain of moisture from the atmosphere differs only in degree from one electrode to another, so that it is possible to bring out the important points without reference to particular electrodes.

Baking Low-Hydrogen Electrodes

A large part of the water in the binders may be removed by baking at temperatures around 100°C. but some remains in combination and requires higher temperatures for its removal.

After baking at 200°C. very little moisture remains but further amounts that can be important in critical circumstances may be removed by baking at temperatures up to 450°C. (Fig. 2).

Beyond this temperature iron powder or alloys in the coating begin to oxidize, and at 500°C. calcium



2—Moisture loss on drying low-hydrogen coatings

carbonate starts to decompose. The final evolution of moisture from the binders takes place at still higher temperatures and it is clearly not practicable to remove this residual moisture.

To facilitate manufacture, other materials containing hydrogen may be added to the coating but these are removed by the baking and present no subsequent problem as does the moisture picked up by the coating from the atmosphere.

To keep the pick-up to a minimum the binder content may be kept low but this method has the disadvantage that the resulting coating may be very fragile.

Moisture Regain

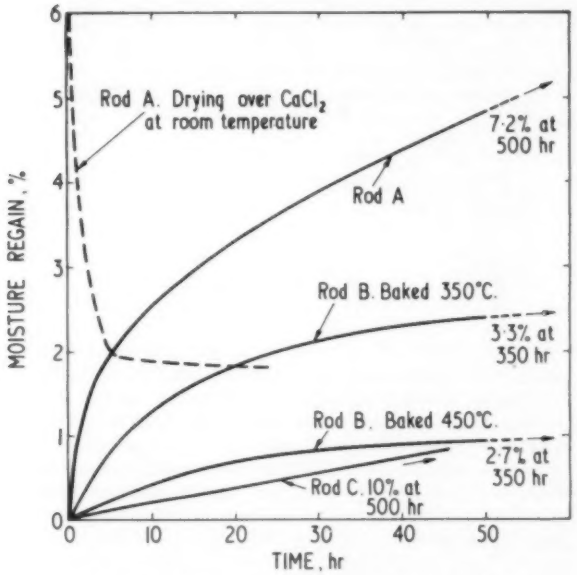
After an electrode has been baked it contains less moisture than it would if it were in equilibrium with the atmosphere.

As soon as the coating has cooled, moisture will begin to recombine with the binder but the rate at which this takes place is dependent on the type of

binder, the permeability of the coating, and the relative humidity of the atmosphere.

Pick-up can therefore be prevented by packing the electrodes in a hermetically sealed container. This protection, however, only lasts as long as the container remains unopened or until it is punctured. The high cost of containers and the need for protection after the containers have been opened has led to the general practice of rebaking the electrodes shortly before they are used.

If they are used before they have cooled completely, it is easy to tell that they are freshly baked because they are warm to the touch. When they are cold one cannot tell how long they have been cold. Once they have cooled, moisture pick-up proceeds first of all fairly rapidly and then at a decreasing rate for a very long time, as may be seen from Fig. 3.



3—Moisture regain at 86% relative humidity and 30°C

It is interesting to note that the initial rate of pick-up is no guide to the ultimate rate. In the examples chosen the electrode with the slowest initial rate of pick-up has gained the most after 500 hr.

A further point of interest is that baking rod *B* at 450°C. reduced the rate of pick-up by comparison with the same electrode baked at 350°C. For practical purposes the pick-up in the first few hours is more important than the ultimate pick-up.

The baking of small quantities is a nuisance, but where a continuous supply is needed it is usual to bake fairly large quantities and then to store them in an oven at about 100°C. until they are required. When the point of use is not near the storage oven, the electrodes are taken to the job in a heated quiver.

It is possible to keep electrodes dry by storing them in a box containing a material such as calcium chloride, silica-gel, or activated alumina to keep the air dry, but it is not easy to tell whether electrodes stored in this manner have been protected continuously since they were baked. Electrodes that have become damp and are then placed in a dry atmosphere will dry quickly but incompletely. Some moisture that remains in combination can be removed only by raising the temperature of the electrode.

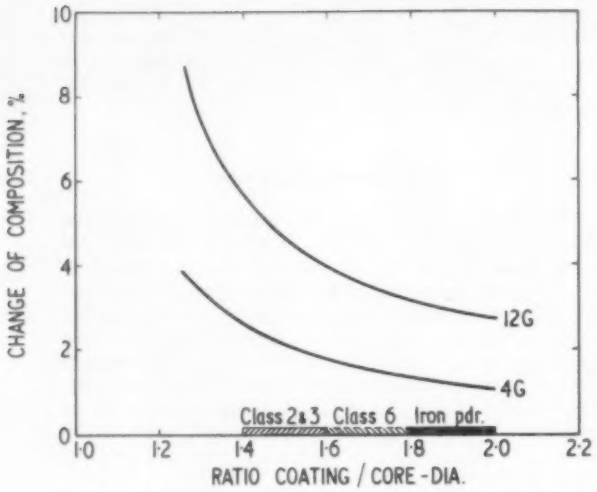
Iron Powder Electrodes

The advantages in ease of operation that may be gained by applying a heavy coating to an electrode have been known for many years but unfortunately early electrodes made in this manner produced far too much slag for satisfactory control of the weld metal. During recent years part of the coating has been replaced by metal powders and substantial advantages in both ease of operation and in control have resulted. Early electrodes of this type were designed primarily to achieve high welding speeds, but recently more attention has been devoted to producing types with greater flexibility of operation.

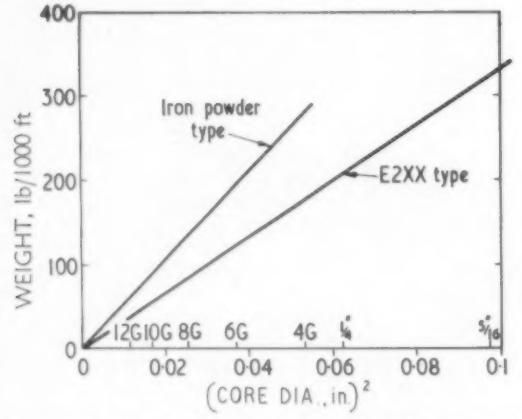
Whereas it has been customary for many years to add small proportions of alloying elements to electrode coatings to modify the weld metal composition, the types of coating found suitable for iron powder electrodes have made it possible to produce alloy steel weld metal deposits from electrodes in which all the alloy constituents are in the coating and in which the coating may even contain additional iron in the form of powder to render its operating characteristics more favourable. It thus becomes possible in many instances to dispense with the use of alloy core wires entirely. It is practicable to produce, for example, 14% Mn steel deposits or 18/8 stainless steel deposits from electrodes in which all the alloys are in the coating. It would be foolish to pretend that such electrodes will eliminate the need for electrodes with alloy steel core wires, since there is some risk that portions of the deposit may deviate from their correct composition should an electrode be used with a damaged coating. Electrodes of this type are however substantially cheaper to produce, and for many purposes would be entirely satisfactory. They therefore offer an attractive alternative to the more conventional type of electrode.

In electrodes of this type full advantage can be taken of the excellent metallurgical qualities of basic coatings because electrodes so constructed have greatly improved operating characteristics by comparison with conventional basic-coated electrodes. These electrodes offer the interesting possibility that the composition of the weld metal may be controlled to a higher degree of accuracy than that of the steel for which they are intended to weld. It is difficult to indicate what degree of variation of weld metal composition would occur in practice when all the possible variables have been taken into account, but it would seem that the composition could be kept within $\pm 5\%$ of the nominal amount of the element, with the possible exception of a few elements which are easily lost in transfer through the arc and which would therefore prove to be unduly sensitive to variations in the welding conditions.

The main cause of variations in weld metal composition is the arc length, but since these electrodes can be employed with a touch welding technique, the chance of an incorrect arc length is greatly reduced.



4—*Change of weld composition for a 0·002 in. change in coating diameter*



5—*Relationship between core wire size and weight of electrode*

Figure 4 shows the dependence of weld metal composition on control of the coating size for different ratios of coating to core-wire diameter. The advantage in this respect of electrodes with high coating/diameter ratios is obvious, though it is offset, to some extent, by the greater difficulty of controlling the diameter during manufacture.

Effective Size of Electrode

A problem to which no satisfactory solution has yet been found arises when comparisons need to be made between iron powder electrodes and conventional types. Comparisons often require that the size of electrode be stated, and it has been convenient in the past to quote the core wire size. This measure has little meaning when there may be as much metal in the coating as half the weight of core wire. In such circumstances the electrode will be effectively more than one size larger than is indicated by its core wire size (Fig. 5).

Both the welding current and weight of deposit per foot of electrode are related to the effective size, and since the optimum design differs widely according to the type of coating a measure of size in terms of pounds per 1000 ft, though not a perfect measure, would have more meaning than gauge size.

Electrode sizes might then be given in the following way:

Present size	*Suggested nominal size*	
12 g	size 40 (lb/1000 ft) or 60 (g/metre)	
10 g	60	90
8 g	90	135
6 g	125	180
4 g	180	270
¼ in.	210	310
5/16 in.	325	500
⅜ in.	450	700

It is proposed that for easy reference electrodes with weights between say 75 and 110 lb/1000 ft should be referred to as 90 lb electrodes and so on. If the true weight were known it would then be easy to see to what extent the true size deviated from the nominal.

Such a scheme would enable iron powder types of electrode to be fitted in without the uncertainty that prevails at present, and it is suggested that serious thought be given to this question.

Acknowledgments

The author acknowledges helpful criticism during the preparation of this paper by his colleagues in the Heating and Welding Department of the A.E.I. Transformer Division.

REFERENCES

1. M. W. Mallett: *Welding J.*, 1946, vol. 25, pp. 396*s*–399*s*.
2. W. P. Van Den Blink: *Welding J.*, 1947 vol. 26, pp. 369*s*–370*s*.
3. P. K. Gledhill: "Final report on investigations into the viscosity of welding slags." B.W.R.A. Report FM 5/20, 1951.
4. D. Séférian: *Sheet Metal Ind.*, 1952, vol. 29, pp. 239–248 254.
5. *Ibid.*, pp. 441–446, 529–532, 540.
6. *Ibid.*, pp. 627–634, 642.
7. D. C. Smith: *Welding J.*, 1959, vol. 38, pp. 377*s*–392*s*.

AUTUMN MEETING, 1960

Welding Metallurgy of the Nimonic Alloys

By J. Hinde, F.I.M., M.INST.W. *and D. R. Thorneycroft*, B.SC., A.I.M., M.INST.W.

The constitution and physical properties of alloys of the Nimonic and Nimocast series are discussed in relation to their influence on welding characteristics.

Effects of the solution and precipitation-hardening heat-treatments used to develop optimum high-temperature properties are correlated with the behaviour of the respective materials under the thermal conditions imposed by welding. The mechanical properties of the parent metals and of the welded joints are described, with particular reference to the effects of the various temperatures attained by the weld itself and by adjacent heat-affected zones. Welding procedures are recommended for both wrought and cast nickel-base high-temperature alloys.

Brazing techniques and materials are also considered, including the possibility of combining the brazing operation with thermal hardening treatments required for certain alloys.

Introduction

THE development of the gas-turbine engine for aircraft propulsion was accompanied by the need for materials to withstand the severe operating conditions created by high inlet gas temperatures and high centrifugal stresses in rotors. During the early development stages, the modified Cr–Ni austenitic stainless steels were utilized primarily for rotor blades on account of their creep- and corrosion-resistance, but in 1941 the introduction of the first of the Nimonic series of wrought Ni-base, creep-resisting alloys provided materials of construction with superior properties at elevated temperatures. The development of these alloys from an 80% Ni–20% Cr alloy has been reviewed by Betteridge.[1] Whilst the first alloy of the wrought series, Nimonic 75, was essentially the original 80/20 Ni–Cr alloy strengthened by a small addition of titanium, succeeding alloys were more complex in composition, and incorporated alloying additions of aluminium, cobalt, molybdenum and other minor elements as a means of improving high-temperature properties. Complementary to the wrought materials are the alloys of the Nimocast series, which were developed in recent years for applications involving the use of cast forms.[2] Table I summarizes the main compositional features of the two groups of alloys of current interest, while Fig. 1 indicates the progressive improvement over the years in the high-temperature strength of the Ni-base alloys.

The high-temperature strength of the first alloy, Nimonic 75, has been substantially exceeded by that of the more highly-alloyed derivatives, but this Ni–Cr alloy has become a standard material for gas-turbine flame tubes in the United Kingdom. The alloy's high degree of scaling resistance and the substantial degree to which it retains its mechanical properties at high temperatures, have resulted, moreover, in its adoption for a number of engineering applications other than in the gas turbine. Attractive features of the alloy are that it can be readily formed by spinning, pressing, or rolling processes, and, moreover, that welding by all conventional methods offers no

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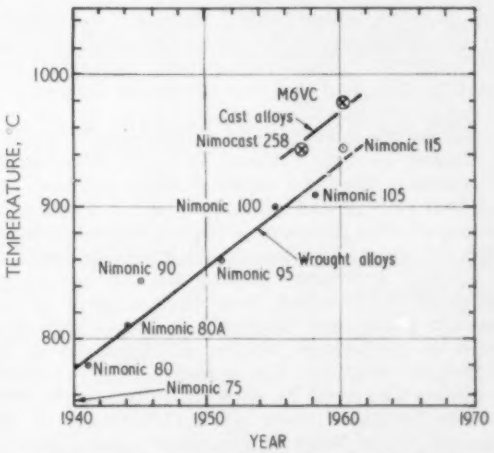
The authors are with The Mond Nickel Co. Ltd., Development and Research Department, London. 589



1—*Temperature for rupture in 100 hr at 10 tons/sq.in.*

Table I

The Nimonic and Nimocast high-temperature creep-resistant alloys*

Wrought alloys

	Nominal Composition, %			
Nimonic	*75*	*80A*	*90*	*105*
C	0·08–0·15	0·1 max.	0·13 max.	0·2 max.
Fe	5·0 max.	5·0 max.	5·0 max.	1·0 max.
Cr	18–21	18–21	18–21	13·5–16·0
Ti	0·2–0·6	1·8–2·7	1·8–3·0	0·9–1·5
Al	—	0·5–1·8	0·8–2·0	4·2–4·8
Co	—	2·0 max.	15–21	18–22
Mo	—	—	—	4·5–5·5
Ni	Substantially balance			

Casting alloys

Nimocast	*75*	*80*	*90*	*242*	*257*	*258*	*713C*
C	0·07–0·15	0·03–0·13	0·07–0·15	0·27–0·40	0·06–0·10	0·17–0·24	0·08–0·20
Si	0·2–0·8	0·2–0·8	0·2–0·8	Si + Mn	0·2–0·8	0·10–0·45	1·0 max.
Mn	0·2–0·7	0·2–0·7	0·2–0·7	1·0 max.	0·2–0·7	0·10–0·45	1·0 max.
Fe	5·0 max.	5·0 max.	5·0 max.	1·0 max.	5·0 max.	2·0 max.	5·0 max.
Cr	18·0–22·0	18·0–22·0	18·0–22·0	18·0–23·0	18·0–22·0	9·5–11·5	11·0–14·0
Ti	0·3–0·6	2·2–2·6	2·2–2·6	0·3 max.	1·4–1·75	3·4–4·0	0·25–1·25
Al	0·1–0·4	1·0–1·4	1·0–1·4	0·2 max.	0·8–1·15	4·6–5·5	5·5–6·5
Co	3·0 max.	3·0 max.	15·0–18·0	9·0–11·0	15·0–18·0	18·0–22·0	
Mo	—	—	—	9·5–11·0	—	4·25–5·75	3·5–5·5
Other elements						0·005–0·02 B	1·0 –3·0 Nb + Ta 0·05–0·15 Zr 0·005–0·015 B
Ni	Substantially balance						

* Nimonic and Nimocast are trade names

problems if the correct techniques are used. Nimonic 75, Nimocast 75, and Nimocast 242 do not normally require a heat-treatment to develop their high-temperature properties, whereas the remaining alloys of the series are subjected to solution- and precipitation-hardening treatments to obtain the higher creep strengths associated with the more complex compositions.

The heat-treatable alloys are characterized by the presence of relatively large amounts of titanium and aluminium (Table I), which combine with nickel to form a precipitation-hardening compound. Such composition, however, generally renders the heat-treatable alloys more difficult to weld by fusion welding processes, and it is recognized that welds should preferably be made in material in the soft condition resulting from appropriate solution or annealing treatments. Optimum properties are attained in the joint only be applying post-weld heat-treatment, as will be discussed in a later section of the paper.

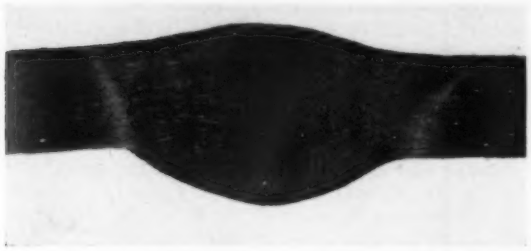
Despite the complexity of their compositions, the heat-treatable alloys have been satisfactorily welded, particularly wrought Nimonic 80A and Nimonic 90, by resistance-spot and -seam welding processes, by flash-butt welding, and by the argon-shielded processes. The use of these processes in the welding of Nimonic alloys for gas-turbine assemblies has been described by Levick,[3] and many elegant welding operations, typical of those which have been applied to the Nimonic alloys, are illustrated by Sandiford[4] in a review of mechanized welding developments in the aero-engine industry. The majority of the welding operations described by these authors are on components fabricated from sheet (commonly of the Nimonic 75 and Nimonic 80A alloys) usually thinner than $\frac{1}{16}$ in.: heavier sections have, however, also been satisfactorily welded, as in the production of Nimonic 80A gas-turbine rings, by the flash-butt process. It should be emphasized that most of the Nimonic alloys were developed primarily for gas-turbine blading, and not until their use was extended to other components of the turbine did the need arise for welding them in sheet, bar, or cast form. As a result of new developments in other branches of engineering, in which advantage has been taken of the unique high-temperature properties of the Nimonic alloys, the alloys have now to be welded (in the fabrication of industrial heat-treatment plant, and of steam plant) in relatively thick sections of plate, tubing, and piping. For these applications, special attention has been given to the welding response, in particular to that of Nimonic 80A and Nimonic 90 and the corresponding casting alloys.

Techniques and brazing alloys are now available[5] whereby Nimonic alloys can in various forms be assembled more advantageously by brazing procedures than by fusion welding. A significant metallurgical factor affecting the success of the brazing operation is the surface condition of the alloy, primarily with respect to freedom from oxide films. Brazing temperatures are generally higher than 1000°C., so that the heat-treatable alloys will be affected by the thermal cycle of the brazing operation.

Welding Metallurgy

Physical properties

Melting ranges for several of the alloys are listed in Table II, from which it is seen that heating at the weld interface, in full-fusion-welding operations, will be to temperatures of at least 1340°C., although lower temperatures will be attained at positions within the



2—*Macrostructure of Nimonic 75 weld, showing heat-affected zones at sides of weld* ×8

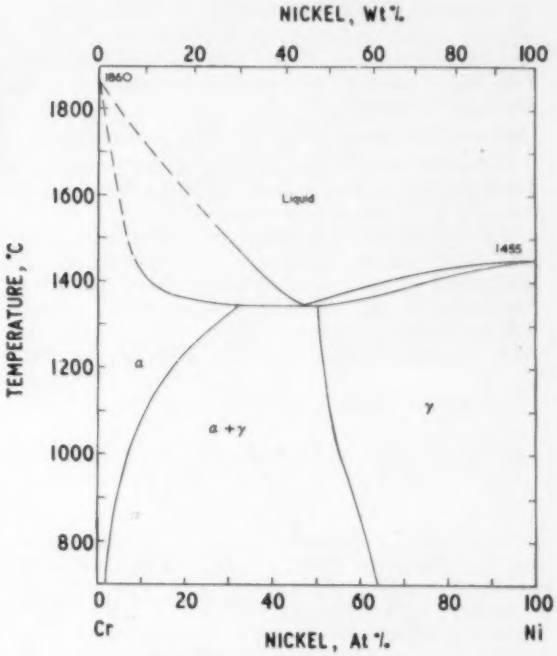
heat-affected zone of the parent material adjacent to the fusion weld. Thickness of section, welding process, the integrated effects on the thermal input of welding speed, welding current, and other welding conditions, and the thermal conductivity and electrical resistivity of the alloy are several of the many factors which combine to govern the width of the heat-affected zone. (Figure 2 illustrates this zone in a Nimonic 75 weld.) As with any group of alloys, physical properties are among the factors which govern welding characteristics. The average physical constants of the Nimonic alloys (included in Table II) show no marked differences among the various alloys of the series. A recent publication presents the welding characteristics of some of the Nimonic alloys, in terms of practical conditions for making sound joints.[6]

Constitution and structure

Information on these factors has been gained during the development of the wrought alloys, but the basic principles will apply equally to the corresponding casting alloys.

Nimonic 75 Ni–Cr-alloy)

Nimonic 75 exhibits the simplest constitution, containing principally nickel, with additions of 20% Cr, 0·3% Ti, and about 0·1% C. Chromium carbide is precipitated from the Ni–Cr matrix after solution-treating at 1225°C. and ageing for several hours at temperatures between 750° and 1000°C. A small increase in hardness is obtained by this treatment, but the alloy is not normally regarded as precipitation-hardening, and for practical purposes is considered to consist of a uniform solid solution of chromium in nickel, characterized by the face-centred-cubic structure of the γ-phase (Fig. 3). As would be expected, the alloy is relatively insensitive to the thermal effect of a welding or brazing operation, the only changes that



3—*Nickel-chromium phase diagram*

occur in the heat-affected zone being a slight coarsening of the grains and a small decrease in hardness. There are, therefore, no metallurgical reasons for post-weld heat-treatment.

The recommended weld metals for argonarc and metal-arc joints also contain approximately 80% Ni, 20% Cr, and in stress-rupture tests, for example, the strength of the joint is comparable with that of the annealed Nimonic 75 alloy.[7] Figure 4 illustrates rupture at 750°C. in a Nimonic 75 test-piece, where the 80/20 Ni–Cr weld metal is obviously stronger than

4—*Position of fracture in welded Nimonic 75 sheet, after stress-rupture testing at 750°C.* ×1½

Table II

Physical properties of some Nimonic alloys

Property	*Nimonic Alloy*				*Nimocast Alloy*	
	75	*80A*	*90*	*105*	*75*	*90*
Melting range, °C.	1390 to 1420	1360 to 1390	1360 to 1390	1340 to 1380	c.1410	c.1380
Specific Heat, cal/g/°C. (20–100°C.)	0·110	0·103	0·110	0·11	*	*
Thermal Conductivity, J/cm.sec. °C.						
at 50°C.	0·132	0·114	0·121	0·108	*	*
at 800°C.	0·260	0·255	0·253	0·230		
Electrical Resistivity, $\mu\Omega$/cm, at 20°C.	109	124	115	130	*	*

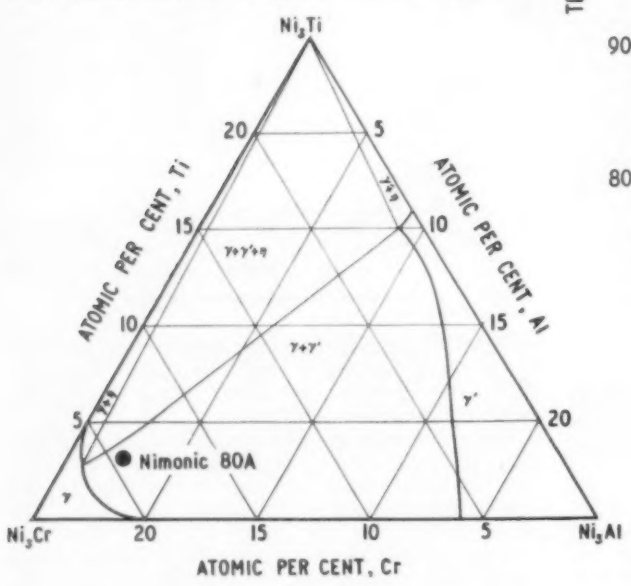
* not determined.

the adjacent alloy. This feature is attributed to the slightly higher carbon content (approx. 0·2% C) of the weld deposit, associated with the special argonarc filler wire,* and leading to carbide precipitation during the stress-rupture test.[1]

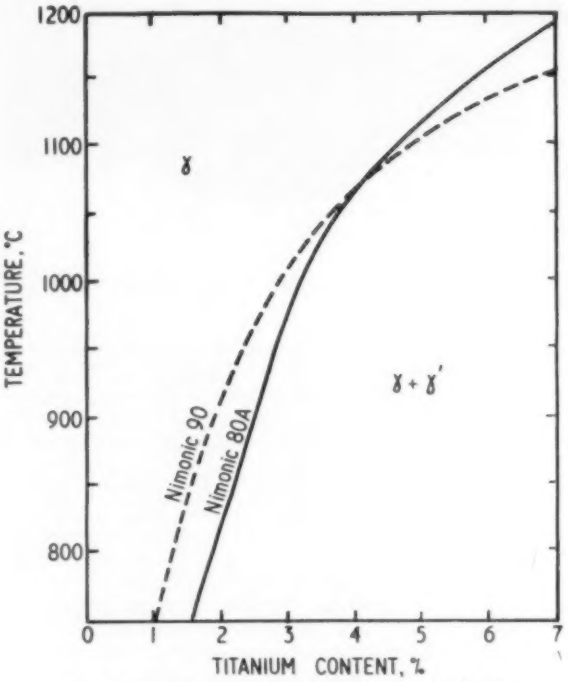
Nimonic 80A and 90 (Complex Ni–Cr-base alloys)

Constitutional studies of these alloys provided an understanding of the fundamental behaviour of all the heat-treatable alloys of the series.

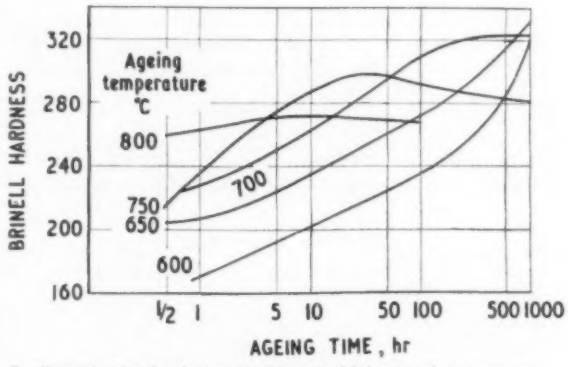
The comprehensive studies of Taylor and Floyd[8] established that the compound of the type Ni_3 (Ti, Al) designated γ' is the precipitating phase that causes hardening in the 80/20 Ni–Cr-base alloys containing significant amounts of these elements. The relevant pseudo-ternary diagram derived by these investigators of cobalt-free alloys, showing the extent of various phase fields in equilibrium at 750°C., is reproduced in Fig. 5. The Nimonic 80A composition is also indicated on this diagram. The γ' compound is completely dissolved in the matrix at temperatures above about 875°C., but re-precipitates as a result of appropriate heating at lower temperatures. The preferred Ti and Al contents of Nimonic 80A and 90 are in the ratio 2:1; the solid solubility limits for these elements, which have been accurately determined by metallographic studies, are compared in Fig. 6, which shows that the solubility of the hardening phase is more restricted in the Co-bearing alloy. Betteridge and Franklin[9] have established that the precipitation of chromium carbide, predominantly at grain boundaries, is also an essential structural feature which, associated with appropriate solution and age-hardening treatments, contributes to optimum creep properties. Solution of carbide occurs at temperatures considerably higher than the solution temperatures for the Ni_3 (Ti, Al) compound; most of the carbide is in solution at 1200°C. and is precipitated at temperatures below 1150°C. Solution-treatment for 8 hr at 1080°C., followed by air-cooling and by age-hardening for 16 hr at 700°C., was finally selected as the heat-treatment giving the best combination of creep properties, although variants have been developed to



5—*Pseudo-ternary phase diagram for nickel–chromium–titanium-aluminium alloys. Isothermal section at 750°C.*



6—*Solubilities of titanium and aluminium in 80% Ni, 20% Cr (Nimonic 80A) and 60% Ni, 20% Co, 20% Cr (Nimonic 90) alloys (Ti/Al ratio 2:1)*



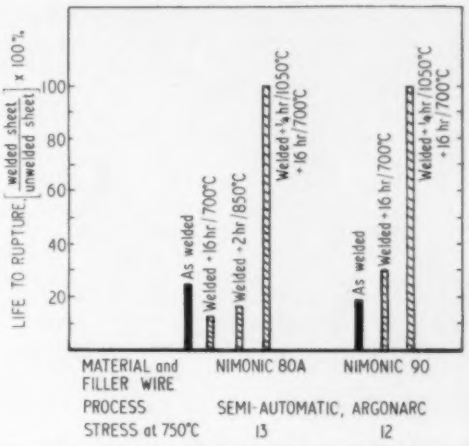
7—*Precipitation-hardening in Nimonic 80A at various temperatures; after solution treatment at 1080°C.*

* BS.2901. Part 1:1957. Filler wire NA.34.

modify properties in relation to the requirements of specific applications.[10] The age-hardening characteristics of the Nimonic 80A alloy are summarized in the series of hardness curves reproduced in Fig. 7.

It would appear from these heat-treatment data that the rates of solution and precipitation are relatively slow, but detailed studies have revealed that solution and precipitation may start within a few seconds of heating to certain temperatures, a finding which is confirmed by observations made on the structure of heat-affected zones in welds.

Clearly, in a full-fusion welding operation, a narrow zone of the parent material is heated to temperatures between ambient and the melting point of the alloy. Thus, in this way, a heat-treatable alloy such as Nimonic 80A or Nimonic 90 will be subjected to a variety of heat-treatments and structural changes. Some aspects of these changes are considered below.



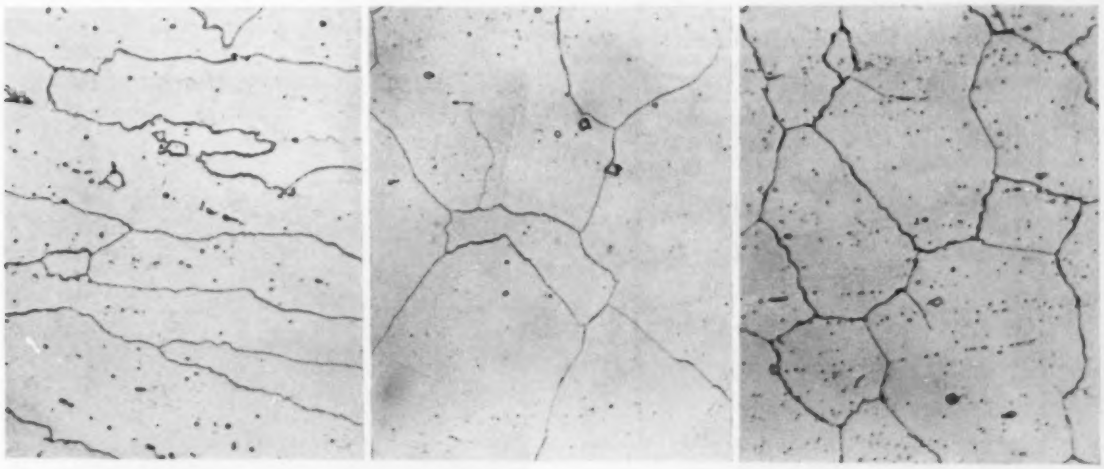
9—*Effect of welding and post-weld heat-treatment on the stress-rupture properties of Nimonic 80A and 90 sheet*

Effects of Welding

Nimonic 80A and Nimonic 90

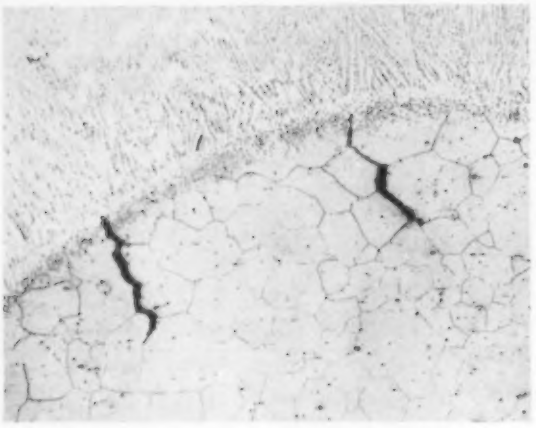
A single-run butt weld is commonly produced in the welding of Nimonic 80A alloy components made from sheet material. Thus, Fig. 8 illustrates typical microstructures at different positions in an argonarc weld. The Nimonic 80A weld deposit is characterized by a columnar grain structure (Fig. 8*a*), in which only a few precipitated particles, possibly of carbide, are visible, whilst in the heat-affected zone immediately adjacent to the weld (Fig. 8*b*) all precipitates, even the carbides, have been dissolved, indicating that this zone has been heated to at least 1200°C. during the welding operation. Remote from the weld (Fig. 8*c*) the characteristic structure of the sheet is unaffected by welding. The weld and heat-affected zone structures have been found to exhibit relatively poor high-temperature properties in Nimonic 80A and Nimonic 90 in the as-welded condition. Stress-rupture data at 750°C., reproduced in Fig. 9, illustrate this effect, and also show that properties are restored by post-weld heat-treatment involving heating at 1050°C., air-cooling, and finally, the customary age-hardening treatment at 700°C. It is deduced from these observations that controlled solution treatment after welding is necessary to remove unfavourable structures induced by the heating and cooling cycles of the welding operation.

A further problem was encountered in making butt welds by argon-shielded processes in relatively thick sections of Nimonic 80A and Nimonic 90. Intergranular cracking occurred in the heat-affected zone, normal to the weld interface, in a region where the temperature probably exceeded 1200°C. as heat flowed from the weld. From the position and nature of the cracking (Fig. 10) it was deduced that the alloy was hot-short under severe restraint (*i.e.*, under the conditions present in thick, tied joints). To withstand these conditions, a weldable grade of the material was produced by slightly modifying the composition in respect



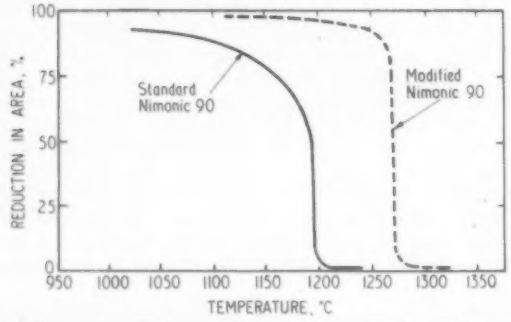
(a) (b) (c)

8—*Comparison between weld zone structures and material remote from the weld in Nimonic 80A sheet, welded by the argonarc process*: (a) *Nimonic 80A weld;* (b) *heat-affected zone;* (c) *zone remote from weld* ×400



10—*Cracking in heat-affected zone of Nimonic 90 plate, restrained during the production of a multi-run butt-weld* ×40

of minor elements, although basic creep properties were slightly impaired. The results of rapid tensile tests at high temperatures demonstrated that the grades with improved weldability also exhibited greater ductility at temperatures near the nominal melting point. This characteristic is illustrated in the curves of Fig. 11. In the tensile tests, small cylindrical samples were heated rapidly by electrical resistance heating, and tensile strain was applied within a few seconds of reaching the test temperature. Such conditions of rapid heating and straining resemble those likely to be present at certain stages of welding, particularly in thick, tied joints. Rapid failure, with little reduction in the cross-sectional area of the tensile test piece indicated poor cohesion or 'hot-shortness' in the structure. As indicated in Fig. 11, hot-shortness was encountered over a wider temperature range in material of unmodified composition—a feature which might explain the sensitivity to hot-cracking found in the heat-affected zones of welds. No abnormal microstructural feature was found to account for this extension of the hot-shortness temperature range.

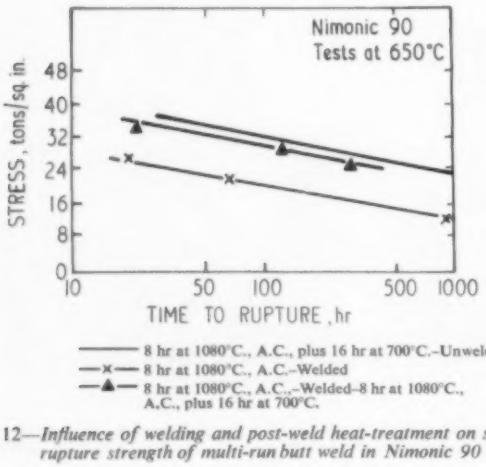


11—*High-temperature tensile-ductility characteristics of Nimonic 90 and of a modified alloy with improved welding response*

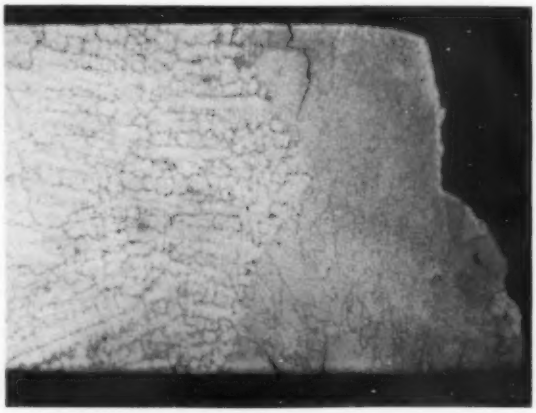
Stress-rupture tests on multi-run welds in $\frac{3}{4}$ in. thick plate of the modified Nimonic 90 alloy, made by the argon-shielded, metal-arc process with filler wire of matching composition, provided additional evidence that the high-temperature strength of the as-welded joint is substantially lower than that of the conventionally heat-treated, unwelded alloy. Relevant stress-rupture data, reproduced graphically in Fig. 12, exemplify the considerable improvement in strength obtained by post-weld heat-treatment involving conventional solution and precipitation-hardening treatments. The interesting feature was that in most tests on the thick-section welds failure was in the weld metal, whereas in the tests on sheet samples, described earlier, failure was generally in the heat-affected zone of the fully heat-treated welds.

In multi-run welds, therefore, it appears that the cast structure of the weld limits the strength of the joint. To obtain further information on this phenomenon a multi-run weld was made in a Nimocast 90 casting using Nimonic 90 filler wire, and was subjected to stress-rupture tests after a full post-weld heat-treatment. Failure occurred consistently in the weld metal; the microstructure of a section through one of the broken test pieces is reproduced in Fig. 13, and shows the two forms of cast structure. The cause of the relative weakness of the weld structure is the subject of current research.

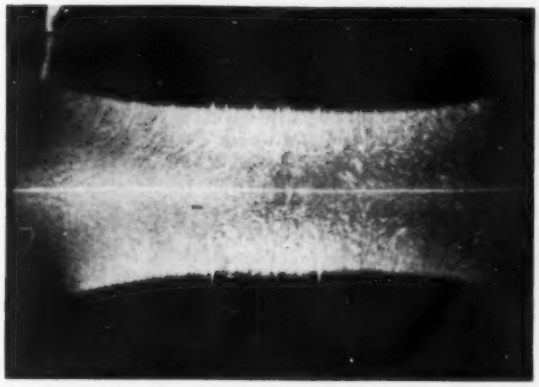
By means of flash-butt welding, welds in Nimonic



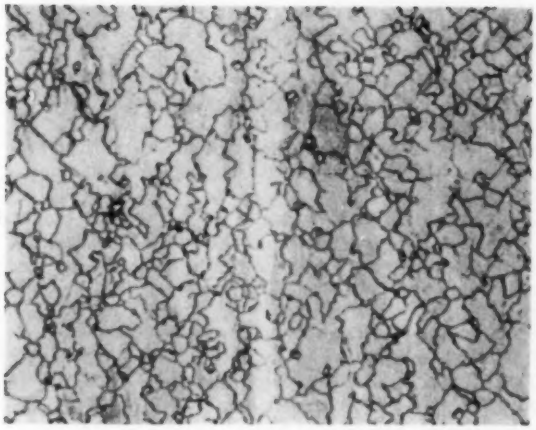
12—*Influence of welding and post-weld heat-treatment on stress-rupture strength of multi-run butt weld in Nimonic 90 plate*



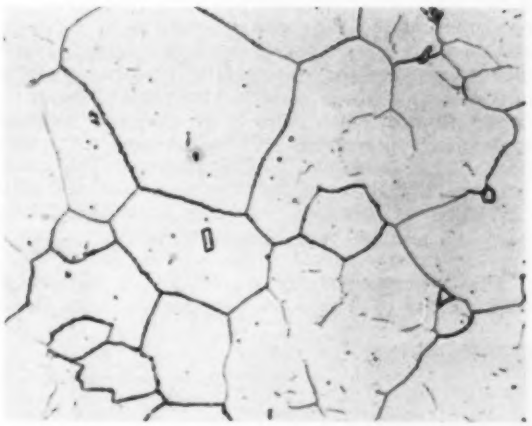
13—*Comparison between cast structures of Nimonic 90 weld metal and Nimocast 90 casting in a multi-run butt-weld made by the argonarc process* ×10



(a)



(b)

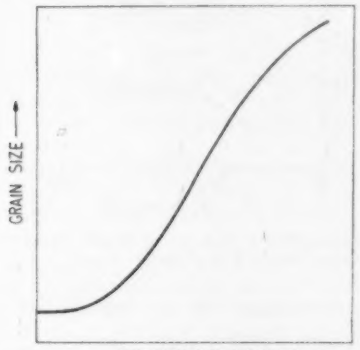


(c)

14—*Flash-butt weld in Nimonic 90 bar*: (a) *Macrostructure* (×3½); (b) *as-welded, and after treatment at 700°C.* (×500); (c) *after heat treatment at 1080°C. and 700°C.* (×500)

80A and Nimonic 90 were obtained, which while exhibiting heat-affected zones, did not have cast weld structures and which, therefore, permitted study of the effect of heat-treatment on the properties of these zones, without interference from weld metal.[11]

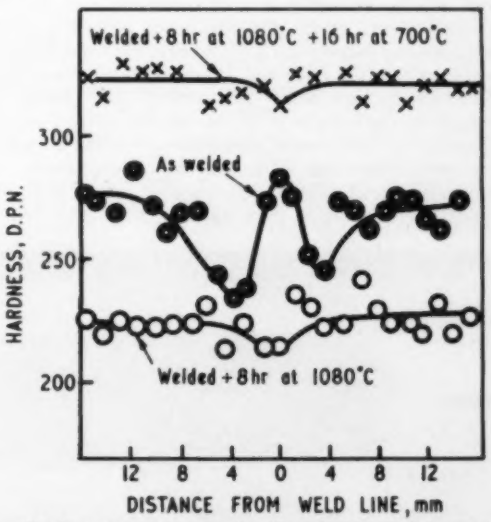
In flash-butt welding, the highest temperature, at the interface, is close to the melting point of the alloy, and the welds are characterized by a wide, heat-affected zone on either side of the junction.[12] Figure 14*a* shows this feature in a welded Nimonic 90 bar. Considerable hot-working is involved at the upset stage of producing the weld: Fig. 14*b* shows the fine-grained structure produced near the weld junction by this operation—no cast structure is present. Grain growth occurs in this region after a post-weld heat-treatment at 1080°C. (Fig. 14*c*), so that the final grain-size is similar to that of the unwelded alloy. Such grain growth is in accord with the established characteristics of the alloy, as is demonstrated by the grain-coarsening/temperature curve reproduced in Fig. 15.



15—*Schematic diagram showing variation of grain size of Nimonic 90 with solution-treatment*

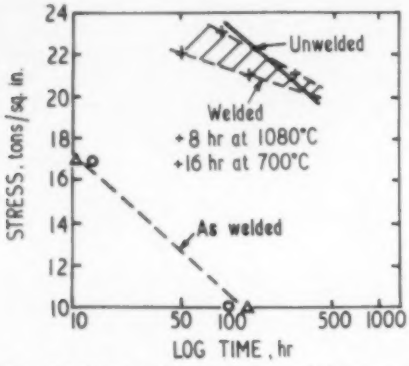
This grain-size/temperature relationship also accounts for the grain-coarsening normally encountered adjacent to arc welds, and indicates the high temperatures reached in the heat-affected zone.

The effects of deformation and welding heat are seen also in the hardness changes that occur in the



16—*Hardness traverse curves for Nimonic 80A flash-butt welds, as-welded and after heat-treatment*

weld zone. Typical hardness-traverse curves, reproduced in Fig. 16 for flash-butt welds in Nimonic 80A bar, which had been solution-treated before welding and given various heat-treatments after welding, confirm the microstructural evidence that welding disturbs the structure of the alloy. Stress-rupture data obtained at 750°C. for welds in $\frac{3}{4}$ in. dia. Nimonic 90 bar (Fig. 17), illustrate the loss of strength in the heat-affected zone, and emphasize the need to apply a full



17—*Effect of flash-butt welding and post-weld heat-treatmen' on stress-rupture strength of Nimonic 90 bar*

post-weld heat-treatment to regain the original properties.

These findings on flash-butt welds, and on the arc welds discussed earlier, are in accord with the established heat-treatment principles which form the basis of the development of optimum stress-rupture properties.

Resistance -spot, -seam, and -stitch welds are in a somewhat special category with regard to structure and the effects of welding, since the cast weld nuggets are surrounded by the parent material, which is therefore subjected at all points to the heat of the welding operation. In the case of Nimonic 80A and 90, the usual effects of solution and precipitation will be present—effects which do not occur with the solid-solution alloy Nimonic 75. Considerable experience in resistance welding Nimonic 75 has demonstrated that, whilst satisfactory welds are readily obtainable, the subsequent performance of the welded component is enhanced by stress-relief treatment. Available experience with Nimonic 80A and 90 components incorporating resistance welds suggests the advisability of post-weld solution and ageing treatments which must, of course, influence the heat-affected zone and weld nugget.

A phenomenon associated with resistance weld nuggets in Nimonic alloys is illustrated in Fig. 18. Molten metal has apparently flowed into cracks arising in the heat-affected zone under the pressure of the welding electrodes. Harris and his co-authors[13] have studied this feature in Inconel X, an alloy somewhat similar to Nimonic 80A, and their experience is that no service failure has ever been attributed to this effect. A survey of this and other features relevant to the quality and properties of resistance welds in the Nimonic alloys is now in progress in Britain.

Nimonic 100 and 105 (Ni–Cr-base alloys)

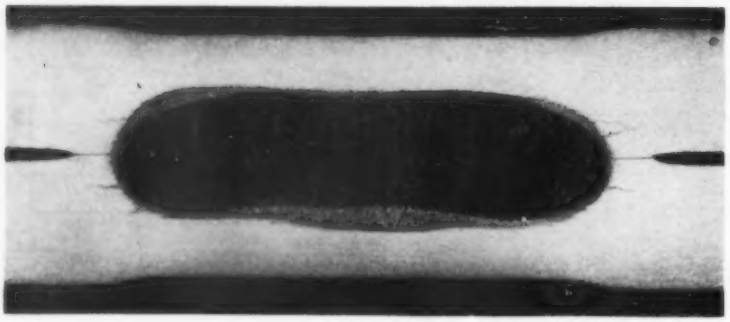
Nimonic 105 (*see* Table I) is a variant of the Nimonic 100 alloy, which it has superseded as a material for gas-turbine blades operating at very high temperatures. Both alloys contain molybdenum and substantially more aluminium than Nimonic 80A or 90, but retain the basic, face-centred-cubic matrix hardened by the γ' precipitate (which is completely dissolved at temperatures above 1040°C.). Relatively large quantities of a complex alloy carbide, which is dissolved only at temperatures above 1150°C., are also present. The standard heat-treatments recommended for the alloys are:

Nimonic 100—Solution-treatment: 1½ hr at 1200°C., air cool.
Ageing treatment: 16 hr at 900°C., air cool.

Nimonic 105—Solution-treatment: 4 hr at 1150°C., air cool plus 16 hr at 1050°C., air cool.
Ageing treatment: 16 hr at 850°C., air cool.

These sequences reflect the more complex heat-treatment required to develop the alloys' special high-temperature properties. Nevertheless, the effect of welding will be primarily to dissolve both carbides and γ' precipitate in those regions of the heat-affected zone where transient temperatures exceed approximately 1050°C. It is to be expected, therefore, that the creep properties of the alloy will be impaired by welding, and therefore that corrective solution and age-hardening treatments will be required after full-fusion welding operations. Details of these requirements have yet to be determined, since there is no extensive welding experience for Nimonic 105, which was developed primarily as a turbine blading material. The other heat-treatable alloys of the series were also originally developed for this role, but subsequently they have been utilized for their special properties in other applications where welding has been involved.

Thus, Nimonic 100 sheet was required in connection with the use of a high-strength sheet material for a



18—*Section of resistance spot-weld in Nimonic 90 sheet, showing characteristic filaments of cast structure at edges of nugget* ×15

creep-resisting application. An examination of argon-arc welds in Nimonic 100 sheet, which were made with filler material of matching composition, revealed an interesting metallurgical phenomenon. Although welds were sound on completion, microcracks were found in the heat-affected zones of the welds after post-weld heat-treatment. It was established that the start of cracking was influenced by the time and temperature of heat-treatment (as depicted in Fig. 19), and that susceptibility to cracking was greatest in the temperature range 800°–950°C. It was found that cracking could be avoided by heating rapidly through this range to higher temperatures, as required for solution-treatment, but the high heating rates needed were attainable only in material less than about $\frac{1}{10}$ in. thick. A similar phenomenon of delayed cracking has been observed in welded Type 347 (18% Cr–12% Ni–Nb) stainless steels[14] in connection with stress-relieving treatments, and has necessitated modifications in heat-treatment schedules. This phenomenon is apparently not displayed by welded Nimonic 105, which is therefore being examined in more detail to evaluate its potentiality as a high-strength alloy particularly amenable to welding.

Casting alloys

Increasing use is being made of the high-strength Nimocast alloys to provide components of a form that is most readily and economically produced by a casting technique. Some of these components are incorporated, by welding, into assemblies of some complexity, usually fabricated in sheet materials, and the welding response of the cast material is therefore of practical interest.

Since the compositions of these alloys reflect the same fundamental principles as those governing the wrought series, the effects of welding would be expected to be similar. The results obtained, under both laboratory and production welding conditions, confirm that the factors involved in the welding response and the effects of welding a cast grade, are indeed similar to those associated with the corresponding wrought alloy. One requirement was to reduce the risk of cracking in the heat-affected zones of Nimocast 80, 90, 257 and 258: success was eventually obtained for the first three alloys by slightly modifying their compositions, but no suitable modification could be found for Nimocast 258, which is difficult to weld.

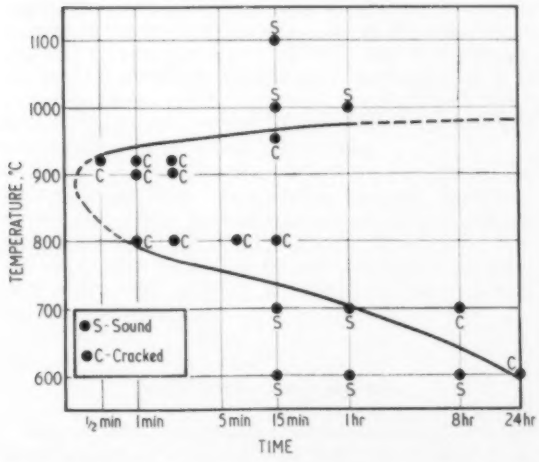
Other considerations must be taken into account in the case of cast alloys. Firstly, the casting must be free from all kinds of porosity to avoid cracking in the heat-affected zone and unsoundness in the weld deposit. Secondly, close control of composition and casting technique is needed to avoid undue micro-segregation, including that of impurity elements which may lead to cracking in heat-affected zones.

Effects of Brazing

Brazing, which requires no fusion of the base material but only of the filler material for the joint, would seem to offer a means of avoiding some of the extreme thermal effects produced by full-fusion welding operations.

Table III gives details of some brazing alloys commonly selected for use with the Nimonic alloys and the relevant heat-treatment schedules. In general, the melting points of the brazing alloys correspond to solution-treatment temperatures for the creep-resistant alloys. There are circumstances, therefore, where heating for brazing may be regarded as part of the normal solution-treatment schedule or, alternatively, as an extension of the solution-treatment, without detriment to the structure of the creep-resistant alloy. Hinde and Perry[5] have reported certain structural features involving penetration of the brazing alloy into the parent material.

The tenacious oxide films formed on the surfaces of the Nimonic alloys, as a result of the presence of Ti and Al, must be removed before brazing to ensure bonding. Precautions are also necessary to ensure that these films do not re-form during the brazing operation. Moisture and oxygen must, therefore, be rigorously

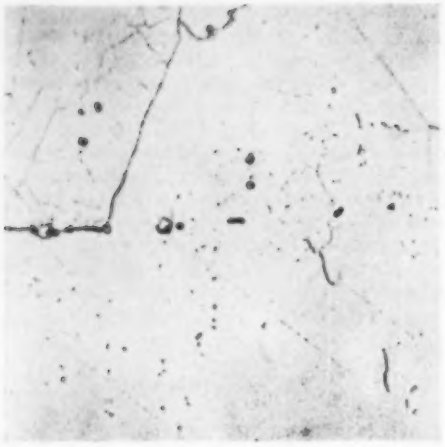


19—*Influence of time and temperature upon cracking in Nimonic 100 sheet heat-treated after welding*

Table III

Some brazing materials for brazed joints in high-temperature alloys

Brazing material	*Melting point, °C.*	*Standard heat-treatments for Nimonic and Nimocast alloys*
Ni/Cr/B (*e.g.* Ni/16Cr/4½Si/3½B/4Fe)	996°, 1027°, and 1120°, depending on precise composition	*Nimonic 80A and 90* 8 hr at 1080°C., air-cool, plus 16 hr at 700°C., air-cool *Nimonic 105* 4 hr at 1150°C., air-cool, plus 16 hr at 1050°C., air-cool, plus 16 hr at 850°C., air-cool *Nimocast 80 and 90* 4–8 hr at 1080°C., air-cool, plus 16 hr at 700°C., air-cool *Nimocast 258* Not normally heat-treated *Nimocast 713C* 2 hr at 1170°C., air-cool
Ag/Pd/Mn (*e.g.* 64Ag/33Pd/3Mn)	1120° and 1200°, depending on composition	
Ni/Pd/Mn (48Ni/21Pd/31Mn)	1120°	
Copper	1083°	



20—*Pressure-brazed joint in Nimonic 90 made with nickel-manganese-palladium filler; almost complete absence of interface after diffusion-treatment at 1200°C.* ×300

excluded from the brazing atmosphere, and vacuum brazing is often the preferred procedure.

More recently a pressure brazing technique, representing a combination of solid-phase welding and brazing principles, has been developed using a Ni–Mn–Pd alloy.[15] The extremely narrow joint achieved is shown in Fig. 20, with only slight distortion of the alloy on either side of the interface, although a post-weld, diffusion treatment at 1200°C., followed by treatments at 1080° and 700°C are required to obtain stress-rupture properties similar to those of the parent material.

Conclusions

With the exception of Nimonic 75 and certain Nimocast alloys, the alloys of the Nimonic and Nimocast series contain titanium and aluminium, in proportion and quantity sufficient to produce hardening by precipitation of the Ni_3 (Ti, Al) compound (the γ'-phase). The precipitation of this phase, and of chromium or alloy carbides, under controlled conditions involving solution and age-hardening heat-treatments, secures optimum properties for these highly creep-resistant alloys.

The thermal effects of welding and brazing operations have been observed to affect the desirable structure of the heat-treatable alloys; in the case of welding, by producing heat-affected zones with poor stress-rupture properties. The properties are substantially restored to the required level, however, by post-weld heat-treatment involving solution and ageing treatments at conventional temperatures. Weld-metal structure and properties are also improved by this treatment.

Heating for brazing can often be part of the standard heat-treatment for the creep-resistant alloy, and satisfactory high-temperature strengths have been achieved under these conditions.

Acknowledgment

The authors are indebted to The Mond Nickel Company Ltd., for permission to publish this paper.

REFERENCES

1. W. Betteridge: "The Nimonic Alloys", Edward Arnold (Publishers) Ltd., 1959, London.
2. "Nimocast Heat-Resisting Alloys." Publication No. 1810. Henry Wiggin and Company Ltd., 1960.
3. R. Levick and P. A. Morgan: *Aircraft Prod.*, 1959, vol. 21, pp. 251–257. (Also "Welding Nimonic Heat-resisting Alloys for Gas-turbine Assemblies." Publication No. 1122. Henry Wiggin & Co. Ltd., Birmingham, 1959,
4. F. G. C. Sandiford: *Proc. Inst. Mech. Eng.*, 1956, vol. 170, pp. 157–184.
5. J. Hinde and E. R. Perry: *Welding*, 1960, vol. 28, pp. 145–154.
6. "Welding, Brazing and Soldering of Wiggin High-Nickel Alloys". Publication No. 1528, 1960. Henry Wiggin and Company Ltd.
7. D. R. Thorneycroft and R. J. Davies: *Proc. Brit. Commonwealth Welding Conf.*, 1957, pp. 319–325. Inst. Welding.
8. A. Taylor and R. W. Floyd: *J. Inst. Metals*, 1951–52, vol. 80, pp. 577–589; *ibid.*, 1952–53, vol. 81, pp. 25–32; 451–464.
9. W. Betteridge and A. W. Franklin: *J. Inst. Metals*, 1957, vol. 85, pp. 473–479.
10. W. Betteridge: *Metal Treatment*, 1959, vol. 26, pp. 45–52
11. F. A. Ball and D. R. Thorneycroft: *Weld Metal Fab.*, 1960, vol. 28, pp. 362–367.
12. E. F. Nippes *et al.*: *Welding J.*, 1951, vol. 30, pp. 585*s*–601*s*.
13. J. Harris, M. D. Bellware, and J. J. Riley: *Welding J.*, 1958, vol. 37, pp. 570–578.
14. R. M. Curran and A. W. Rankin: *Welding J.*, 1955, vol. 34, pp. 207–213.
15. British Patent Appl. No. 12456/59.

AUTUMN MEETING 1960

Welding Problems Associated with Nuclear Fuel Elements

By A. F. Taylor, B.SC., A.I.M.

For economical operation of nuclear power stations, fuel elements must be designed to give maximum life between discharges and this imposes a severe condition for the integrity of the welded end seals. For operation at higher temperatures than is possible with the magnesium alloys used at present, stainless steel or the less common materials such as beryllium, niobium, and zirconium must be considered.

This paper considers the problems associated with the development of welding techniques for sealing present and future elements to a stage where an automatic process can be used on a production scale. The end seal is not the only application of welding in fuel element manufacture, as attachments and supports or the fuel itself also demand welds of high integrity.

THERE are now many nuclear reactors in operation in the United Kingdom, ranging from small experimental piles to the large power producing reactors. At present, the gas-cooled, graphite moderated reactor of the Calder Hall type is the mainstay of the British nuclear power programme, but other types, such as the advanced gas-cooled reactor and the fast fission breeder reactor, are being developed to reduce the cost of nuclear power.

Although many welding problems are entailed in the construction of these reactors, their satisfactory operation ultimately depends on the integrity of the fuel elements, for any failure would cause a temporary shut-down with associated loss of output. For economical operation of the gas-cooled reactors, it is essential to keep the failure rate below 0·1% per year, whilst several failures in rapid succession could lead to complete closure of the reactor.[1] Thus the main aim of welding development is to devise seals that will not prove detrimental to fuel element life.

The use of ceramic fuels is expected to overcome the distortion problems associated with metal fuels and would also allow increases in operating temperature with consequent gains in efficiency. This means that the magnesium alloys in use are no longer suitable, and alternative canning materials of high melting point are required.

Fuel Element Requirements

Before considering the problems associated with the development of a welded end seal, it is desirable to reiterate, briefly, the functions of a fuel element and the main parameters that affect its design.

In a reactor the fuel undergoes fission, liberating heat, which is ultimately converted to useful power, and producing radioactive by-products. As it is necessary to confine the fission products and prevent reaction of the fuel with the coolant the fuel is sealed in a container. The choice of material for the container is governed by the following factors:

(i) Neutron capture cross-section should be low
(ii) No reaction with fuel
(iii) No reaction with coolant
(iv) Adequate mechanical strength at operating temperature
(v) Ability to be formed into the desired shapes
(vi) Weldability.

To provide efficient heat transfer from the fuel to the coolant, good thermal contact between fuel and can is necessary, combined with an adequate radiating surface. The latter may be achieved either by using thin fuel sections in the form of plates, tubes or small diameter rods, or by the use of a finned can. Whichever design of fuel element is chosen, some provision must be made to support it in the reactor in a manner that will allow easy extraction on completion of its irradiation. This demands some attachment to the fuel element; also additional fixtures, such as anti-bowing vanes, may be required to limit possible distortion. In all cases, the amount of material used must be carefully controlled to limit neutron capture and to avoid undue interference with the coolant flow characteristics.

For present thermal reactor applications, the fuel must be hermetically sealed in its container, and

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detailed control is exercised over all stages of can and cap manufacture. Thus, during assembly, the integrity of the fuel elements will depend upon the adequacy of the end seals, and it is not only necessary to develop suitable welding techniques but also to develop inspection methods to determine weld quality.

Welding of Magnesium Alloy Cans

The development of welding techniques for the early Calder Hall fuel elements has been described previously[2,3] but the continual quest for improvement and the demand for a longer irradiation life, particularly for the civil reactors now being built, have already led to many refinements. New techniques are also being investigated.

End seal welding

End seal designs in use at present are all argonarc edge welds of a dished end cap, a typical example being shown in Fig. 1. This basic design has now been

1—Typical Calder fuel element end seal

in use for a number of years and has proved satisfactory during this time, but refinements to the welding technique have been made periodically so as to improve quality or consistency.

Weld cracking

The alloy known as Magnox, selected as the can material for Calder fuel elements, was known to have a slight susceptibility to weld cracking and this governed the choice of end seal design and technique. However, it was found, at a later stage, that surface microcracking could still occur and was not attributable to any changes in composition. Detailed observation showed that this cracking was associated with arc fluctuations such as were indicated on oscillograms by increased arc voltage, delayed reignition of the positive half-cycle, or complete rectification; completely crack-free welds were always obtained with a perfectly stable and quiescent arc. Metallographic examination of the welds showed that these were hot cracks, caused by arc fluctuations partially remelting areas of the weld such that the cooling stresses were increased locally.

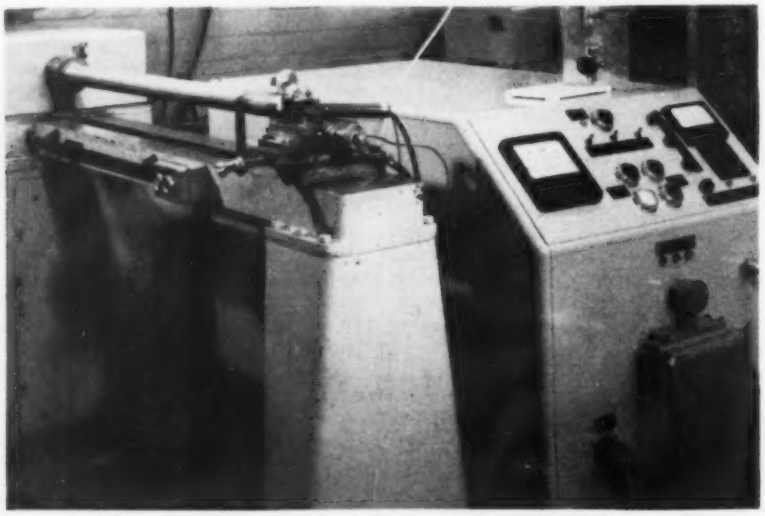
A detailed reassessment of the equipment and technique was instituted to improve arc stability without increasing rejects due to other causes. These investigations led to a number of modifications, the most important being:

(i) Modification of the power source, incorporating a timed pulse surge injector and adjusting the o.c. voltage of the tranformer to 55 V
(ii) Rigid exclusion of draughts

Table I

Welding conditions for Magnox end seals

Power Source	a.c. transformer 55 V o.c. with timed-pulse surge injector and d.c. suppressor
Torch	Air cooled with $\frac{3}{4}$ in. bore gas shield
Electrode	$\frac{1}{8}$ in. dia. 2% thoriated tungsten
Argon/Nitrogen Flow Rate	Up to 6 litres/min
Welding Current	60 amp
Initial Arc Gap	<0·005 in.
Delay to Establish Weld Pool	4–6 sec
Welding Speed	~18 in./min
Second Arc Gap	0·045–0·055 in. after one revolution plus overlap
Crater Elimination	After 2nd revolution plus overlap reduce current and extinguish arc



2—Prototype automatic welding machine for Magnox end seals

(iii) The addition of approx. 0·15% N to the argon (99·9% pure) and using the minimum flow rate consistent with adequate shrouding
(iv) Electrode setting to permit accurate tracking of the weld joint and to provide close control over the arc gap
(v) Crater elimination, obtained by reducing the current before extinguishing the arc.

With these modifications and closer control of all the variables, a revised technique was established, as shown in Table I. The welding sequence was automatic and welding was done horizontally with the torch rotating and the can fixed. However, a new machine was developed later, of the type shown in Fig. 2, where the can is rotated relative to the torch and, to fit in with production line requirements, vertical welding is employed.

Strength of weld

With the design of joint used, the effective depth of penetration is considerably less than the depth of melting, owing to the persistence of an oxide film at the interface. Even with a V groove preparation it is possible to obtain only an average penetration of 0·040 in. with 0·060 in. wall thickness of cap and can, and thus the strength of the end seal is limited. It may be necessary to strengthen this end seal so that it can withstand the distortion resulting from the longer irradiation times demanded for economical power production. This could be done mechanically by using a threaded end cap or by pressing the can neck into grooves on the end cap in the same way as the can body is locked onto the fuel rod.

With the present design of end seal, the effective depth of penetration could be increased by preventing the formation of an oxide 'tail' at the root of the weld, and this suggests the provision of an argon backing. However, there are practical difficulties in doing this when making the final weld of a fuel element, and other means must be considered. Another approach is to use a different groove preparation so that the normal argon shrouding and arc cleaning action can prevent undue oxidation at the interface. Development along these lines showed that a U-groove preparation would give the desired effect and that a mean depth of penetration equal to the can wall thickness could be obtained. To achieve this result it was necessary to modify the technique so that the tip of the electrode was kept down in the groove, and was withdrawn only during crater elimination on completion. Whilst this could be done fairly readily on a semi-manual basis, automation of the sequence made it more difficult to ensure melting to the bottom of the groove while avoiding the electrode touching the molten pool, particularly when phasing the current decay with electrode withdrawal.

Other possible means of obtaining increased penetration are by adding filler wire separately or as a consumable electrode. The feasibility of the former method has been shown (a typical section is shown in Fig. 3) but the fine-wire technique presents many more difficulties on this size of weld, and development is still in its infancy.

3—*Filler wire weld in Magnox* ×30

Inspection

Non-destructive methods of testing the welds are limited to visual inspection, leak testing, and radiography. However, none of these techniques will give a reliable means of determining depth of penetration; it is because of this that automatic welding is used so that destructive examination of $<0{\cdot}5\%$ of the welds will permit quality control.

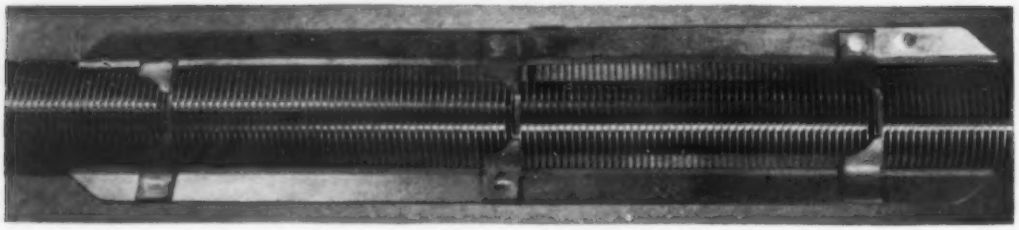
All welds are submitted to non-destructive inspection, and gross defects such as unevenness, pin-holes, blow-outs, and inclusions, are detected by visual examination. Mass spectrometer testing indicates leaking fuel elements and radiography will show inclusions and blow-holes.

The cause of these defects may be many and varied, and an essential part of production control is to determine the reasons for their occurrence. Where a given defect occurs consistently on every weld it is usually easy to detect the cause, but as the percentage of defects decreases a systematic investigation becomes necessary. The following are some examples of how defects arise:

(i) An uneven weld may be due to mechanical faults of the equipment, such as inaccurate tracking of the electrode or an eccentrically placed electrode in the gas shroud, both of which may give rise to inadequate argon shielding. Electrical faults may affect the timed delay at the start of the weld and give excessive melting at this point
(ii) Blow-holes may be due to inadequate drying or cleaning of the components, moisture entrained in the shielding gas, the amount of hydrogen in the metal, mechanical entrapment, or gaseous products from defects in the metal
(iii) Pin-holes can be a stage beyond a blow-hole, *i.e.*, the path of an escaped gas bubble.

Resistance welding

Although the end seal is the most important welding operation on the fuel element other welding operations are required for the attachment of such items as anti-bowing vanes of the type shown in Fig. 4. The use of argonarc welding for this type of fixture would be confined to manual welding but, as an adequate assessment of the weld cannot be made solely by non-destructive examination, an automatic process was preferred and resistance spot welding was selected. It is important that copper contamination of the Magnox should be avoided and particular attention was paid to this point during early trials. Regardless of any precautions taken, contamination invariably occurred and could not be completely removed by simple mechanical cleaning such as wire brushing. The



4—Splitter and brace spot welded assembly

only effective technique was gouging, and this removed a considerable amount of material from the surface, thus weakening the weld. The only alternative appeared to be the use of an interlayer between the electrode and the Magnox, and various materials were tried in the form of electrode tips, electrode plating, and loose shims. To obtain consistent results it was necessary to renew the interlayer at frequent intervals and because of this a 0·003 in. thick mild steel shim was found to be the most suitable.[4] The resultant weld is unlike a conventional spot weld in that fusion extends to the surfaces and thus control tends to be more difficult.

Beryllium Welding

The Atomic Energy Authority is building an experimental advanced gas-cooled reactor (A.G.R.) which will permit higher operating temperatures with improved efficiency. A new type of fuel element will be used, consisting of UO_2 fuel canned in 0·040 in. thick beryllium, the overall size being approximately 0·4 in. dia. by 13 in. long.

Properties

From the nuclear aspect, the main attraction of beryllium is that it has the lowest neutron capture cross-section of all metals, coupled with a reasonably high melting point. The physical properties of importance in welding are given in Table II and are shown in comparison with some other materials. The most noticeable differences are its high specific heat and high latent heat of fusion.

The disadvantages of beryllium from the welding standpoint are its high reactivity towards oxygen and nitrogen and its metallurgical structure. Its reaction with oxygen is similar to that of aluminium in that it readily forms a protective and tenacious oxide film. The crystal structure of beryllium is close-packed hexagonal and its anisotropy gives poor ductility at room temperature and just below the melting point under triaxial stressing. Considerable attention must therefore be paid to fabrication methods that will give the most suitable structure. These have been discussed in detail elsewhere.[5]

In addition to these problems there is a serious health hazard associated with the inhalation of finely divided beryllium or its compounds, and the dust concentration of the atmosphere must be kept below 2 μg/cu.m.

Welding investigations

When the decision was made to develop a beryllium fuel element, American reports[6,7] suggested that the only satisfactory joining techniques were hot pressure welding, diffusion bonding, or braze welding with Al–Si fillers. None of these techniques appeared to be

5—Beryllium welding equipment

Table II

Physical properties of beryllium compared with other metals

Property	*Beryllium*	*Magnesium*	*Aluminium*	*Copper*	*Iron*	*Uranium*
Melting Point, °C	1280	650	660	1036	1535	1133
Specific Heat, cal/g/°C	0·52	0·24	0·21	0·09	0·11	0·028
Latent Heat of Fusion, cal/g	260	89	95	51	65	20
Thermal Conductivity, cal/sec/sq.cm/°C	0·38	0·38	0·53	0·92	0·18	0·06
Coeff. of Linear Expansion, μin./in./°C	12·4	26·0	23·9	16·4	11·7	14
Electrical Resistivity, μΩ/cu.cm	4·0	4·4	2·65	1·68	9·7	30

attractive for fuel element sealing and it was decided to concentrate work at Springfields on the inert-gas shielded-arc welding technique.

Both metallurgical and safety considerations demand that welding shall be conducted in a sealed chamber, and early work was carried out in a glove box purged with argon. Experiments in the glove box involved making edge and butt welds in sheet under flowing argon, and in common with other workers[8] it was found that both transverse and longitudinal intergranular cracks occurred in the fusion zone, although the extent of the longitudinal cracks could be reduced by increasing the welding speed. However, limitations of this equipment led to the construction of a vacuum chamber, of the type shown in Fig. 5, which would allow better control over the atmosphere purity and provide better mechanical handling equipment. At this stage work was concentrated on the welding of end seals suitable for fuel elements, commencing with edge welds of a simple dished end cap.

As with other metals, an important prerequisite for good-quality argonarc welds is the use of a satisfactory cleaning technique, and therefore several methods were investigated. All specimens were degreased and then cleaned by wire brushing, pickling, or electropolishing. Satisfactory results could be obtained in all cases, but great care was needed in washing and drying after the wet cleaning methods to avoid porosity in the welds. Because of this, and the greater simplicity of mechanical cleaning as a production operation, wire brushing was adopted as the preferred technique.

With the components clean, it is then necessary to prevent contamination during welding. Preliminary work had shown that a vacuum purged chamber was the best means. The procedure adopted is to seal the components inside the chamber, which is then evacuated to 5×10^{-3} mm Hg and filled to atmospheric pressure with argon straight from the cylinder. It is important to avoid any partly-trapped spaces within the vessel which cannot be evacuated thoroughly, and it was found that electrical leads to the electrode could be a source of air contamination. To avoid this, normal insulation was removed and replaced by a loose insulating sleeve open at both ends of the lead.

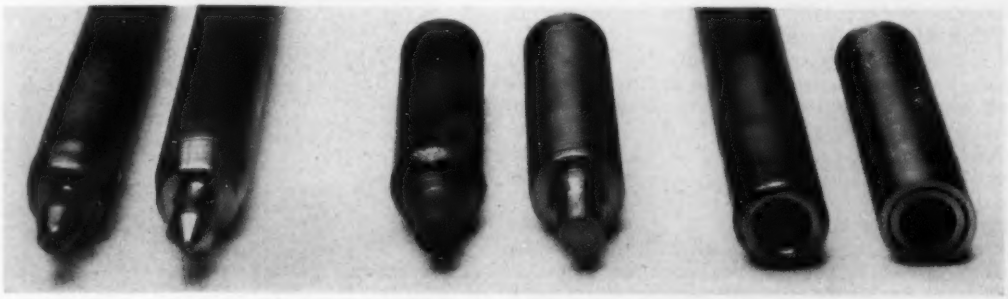
Initial welding trials were confined to edge welds and a variety of power sources was tried. Direct current of both polarities gave unsatisfactory results and, as may be expected from a consideration of the properties of beryllium, an a.c. composite power unit was preferred. At a later stage it was decided to weld in a helium atmosphere as there was a requirement for the interspace between fuel and can to be filled with helium for leak detection and to provide good heat transfer in service. The change to helium made arc striking extremely difficult and, even when it was established, the arc was very unstable. Timed-pulse surge injection gave some improvement but satisfactory results were obtained only with a transformer of 115 V o.c. coupled with a condenser bank for d.c. suppression and an h.f. unit; 2% thoriated tungsten electrodes were also necessary.

Improvements to the equipment and the use of a static atmosphere allowed the production of crack-free welds provided that the welding speed was not too low; 20–25 amp at approx. 6 in./min gave the best results. Lower welding speeds could be used in argon without the occurrence of cracking, probably because of the lower thermal conductivity of this gas (about $\frac{1}{10}$ that of helium) and therefore slower cooling rates. The arc gap setting was found to be critical in that settings of less than 0·020 in. resulted in early contamination of the electrode with beryllium and consequent lowering of its melting point, whilst settings greater than 0·070 in. gave rise to arc instability. Arc gap settings of 0·030–0·035 in. were found to give the best compromise. A crater at the end of the weld must be avoided, as this would produce a local decrease in penetration, and of the various methods tried stepped reduction of the current was preferred.

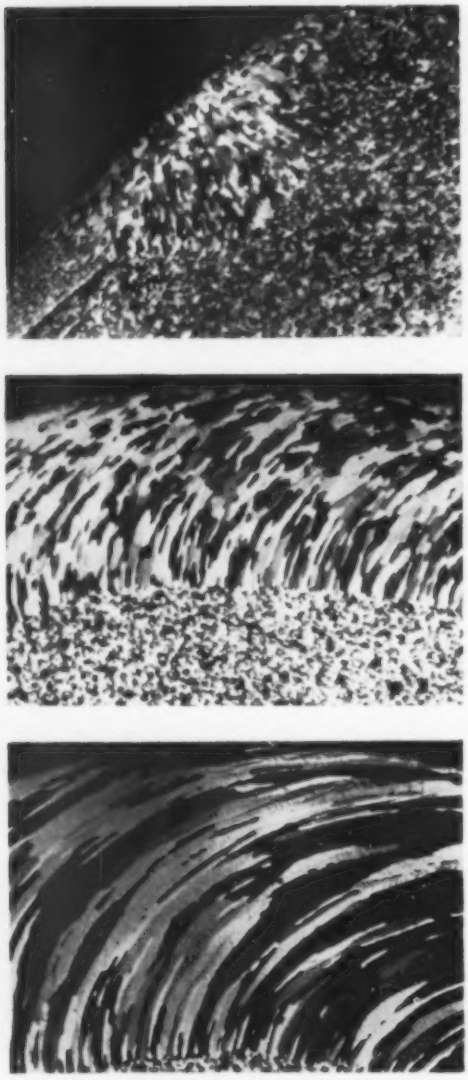
The original investigations were concerned mainly with edge welds but other possible end seals designs have also been considered; some of these are shown in Fig. 6. Crack and leak free welds can be obtained with all designs of joint shown.

Examination and inspection of welds

A cross section of a spigot butt weld is shown in Fig. 7*a*, which shows that the effective penetration is equivalent to the tube wall thickness. This section should be considered in conjunction with the longitudinal section of a weld (Fig. 7*b*) where the columnar structure of the weld bead is more apparent. The importance of careful control of the welding conditions is demonstrated by the longitudinal section (Fig. 7*c*) where excessive heat input has given a very coarse columnar structure. All these photographs show welds made in fine-grained material produced by the extrusion of loose sintered compacts. Where coarse-grained cast material is used, the grain size of the weld bead is proportionately larger.



6—Typical beryllium end seals



7—*Sections of beryllium weld:* (a) *Transverse* ×20; (b) *longitudinal* ×60; (c) *longitudinal* ×60

To evaluate the strength of the end seal, end cap push-off tests have been made at room temperature. Breaking stresses of 14·5 tons/sq.in. have been obtained, fracture normally occurring at the junction of the fused zone and the tube.

Non-destructive examination of the welds was initially limited to visual inspection and mass spectrometer leak testing, but recent improvements in radiographic techniques suggest that the detection of subsurface voids and inclusions will now be possible. Meticulous control of the welding is essential and the human element must be reduced to the minimum at all stages. Quality control can then be exercised by the destructive examination of a small percentage of the welds.

The work has shown that although beryllium has a high cracking propensity, successful autogenous fusion welds can be obtained by careful attention to the material, design, and welding technique. The equipment shown in Fig. 5 provides automatic control of the weld sequence, which will permit pilot production at the rate of 1,000 welds per week and allow a detailed assessment of the consistency of the process.

Stainless Steel Welding

Although it has a relatively high neutron capture cross-section, stainless steel is an attractive canning material, since it can be produced in very thin sections of adequate strength. It is a conventional material and there is an abundance of information on its production, fabrication, and properties. However, in the thin sections required for fuel elements, inclusion size becomes important and modifications to commercial practice are necessary to produce material of adequate cleanness.

It is intended that a proportion of the first A.G.R. charge will consist of fuel elements canned in stainless steel approx. 0·4 in. diameter and 0·010 in. thick.

Welding investigations

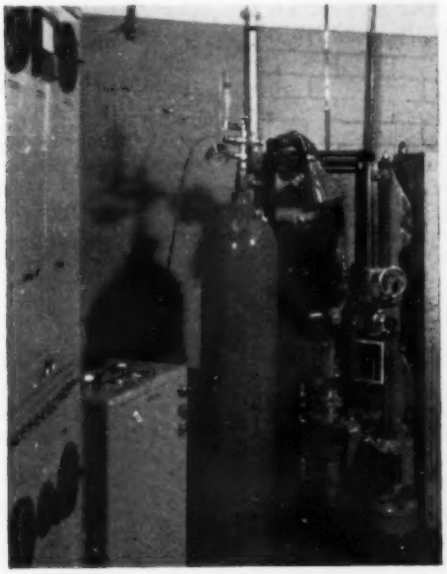
Various compositions of steel are under consideration and, although 18/8/1 is high on the list, it is probable that another alloy with better corrosion resistance to CO_2 at the service temperature will be selected.

Whereas other canning materials have severely limited the choice of joining techniques that can be used, a variety of techniques are suitable for stainless steel in this application. Brazing of high-temperature materials is feasible but possible incompatibility or corrosion problems with these alloys have resulted in more emphasis being given to welding techniques. Argonarc welding, resistance seam welding, and electron beam welding have been considered.

Electron beam welding trials have shown that apart from the better appearance of the weld it has no advantage over argonarc welding. Equipment at present available is a useful experimental tool in the hands of a skilled operator but has not yet reached the stage of development where it can be readily adapted as a production unit.

8—*Resistance seam welded and argonarc welded double end seal in stainless steel*

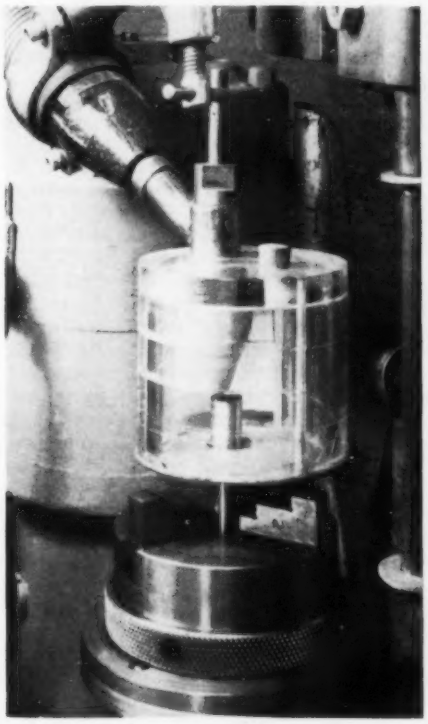
Both argonarc and resistance seam welding techniques are being developed and a duplex end seal is being considered, as shown in Fig. 8. Many other end seal configurations have been investigated but the dished end cap is the only one that will permit both methods to be used. Equipment and procedures for seam welding the end seal are being developed, and work at Springfields has concentrated on argonarc welding.



9—*Automatic argonarc welding equipment for stainless steel*

Early work on 0·010 in. thick 18/8/1 steel showed the difficulty of obtaining consistent arc striking at the low currents (~4 amp) used, and a 3-phase rectifier set was built incorporating a spark starter developed for low-current d.c. arcs.[9] This overcame the difficulties encountered provided that a sharp pointed electrode was used and reground at frequent intervals. A lathe was modified to provide the welding jig and to allow maintenance of a constant arc gap with accurate tracking of the weld joint, and a small Perspex shroud was fitted around the torch to provide adequate argon shielding. The equipment complete with automatic weld sequence control is shown in Figs. 9 and 10.

Components were degreased and wire brushed before welding and it was essential not to have greater than 0·0005 in. clearance between cap and can for satisfactory results. Extra argon shrouding was necessary to prevent oxidation at the interface, which reduced the effective penetration. The final procedure adopted was to set the arc gap to 0·020 in. and with an argon flow rate of 4 litres/min an arc was struck at 4 amp. After a few seconds delay, the can was rotated to give a welding speed of approx. 5 in./min. When the weld had been completed the current was reduced before the arc was extinguished so as to avoid crater formation.



10—*Stainless steel welding head*

Miscellaneous Problems

This paper has so far considered the three major current development programmes at Springfields for which detailed welding techniques had to be specified for the production of fuel elements for gas-cooled reactors. Joining techniques for other materials suitable for fuel element applications have also been investigated. Higher operating temperatures or different coolants demand materials such as niobium, vanadium or zirconium and welding methods for these have been established. Niobium and vanadium have been used for the fast reactor fuel elements at Dounreay.

Inert-gas shielded-arc welding of uranium has been investigated as an alternative means of obtaining long lengths of fuel and also to seal fuel tubes. In the former case, manual welding with filler wire additions has been carried out in a glove box, and the findings are in general agreement with those of other workers.[10] The sealing of fuel tubes necessitates the making of a dissimilar metal joint, since the end plug must be a

11—*Zirconium end plug in a uranium tube:* (a) *before welding;* (b) *after welding*

12—*Sectioned model of an irradiation specimen*

non-fissile material to avoid over-heating. Both zirconium and niobium have been used as end plugs, and a typical uranium–zirconium weld is shown in Fig. 11. Owing to the difference in melting points of the two materials it is necessary to position the electrode over the end plug.

Apart from the development of production techniques for sealing fuel elements there is also a requirement for the fabrication of special test fuel elements for both out-of-pile tests and irradiation tests in Materials Testing Reactors. These may be comparatively simple containments of fuels or more complicated assemblies such as that shown in Fig. 12. This is a cutaway model of a small fuel element double contained in stainless steel sheaths. Four 11-ft long thermocouples are attached to the fuel element and are led out through a high-temperature brazed seal on the inner containment. All joints must be leak tight to vacuum and pressure standards, and extremely tight dimensional tolerances must be maintained at all stages. These requirements are essential to obtain the maximum amount of information from an irradiation test.

Conclusions

The development of welding techniques for specific fuel elements has been described to indicate the nature of the problems encountered, and the work at Springfields can be considered under three broad headings:

(i) Development of techniques for specific designs of fuel elements
(ii) Systematic investigation of production difficulties
(iii) Long-term work to provide basic information.

The suitability of the end seal of Calder fuel elements has been proved in reactor operation but the desire to increase fuel element life calls for the development of better end seals. For more highly rated fuel elements other materials are required and new techniques may have to be developed.

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REFERENCES

1. L. Owen: *Brit. Welding J.*, 1959, vol. 6, pp. 197–204.
2. L. M. Wyatt and F. S. Dickinson: *Weld. Metal Fab.*, 1957, vol. 25, pp. 378–396.
3. I. H. Morrison and A. F. Taylor: *Nuclear Power*, 1958, vol. 3, pp. 217–218.
4. British Patent No. 1664/58.
5. L. R. Williams and P. B. Eyre: *Nuclear Eng.*, 1958, vol. 3, pp. 9–18.
6. D. C. Martin: "The Metal Beryllium", American Society for Metals.
7. R. E. Monroe *et al.*: U.S.A.E.C., B.M. 1–830, Mar. 1953.
8. N. F. Eaton, J. Skinner, and A. J. Martin: *Weld. Metal Fab.*, 1960, vol. 28, pp. 46–52.
9. M. Waller: *Brit. Welding J.*, vol. 5, p. 407.
10. J. R. C. Gough and D. Roberts: *Brit. Welding J.*, 1957, vol. 4, pp. 393–403.

AUTUMN MEETING 1960

Cracking Tests for Assessing Weldability

By J. C. Borland, A.I.M.

The paper reviews the many types of cracking test that have been devised to assess weldability, and discusses their characteristics and limitations. Details of each test described are given in an appendix, and there is an extensive bibliography.

A LARGE number of tests have been devised for assessing the cracking tendency of welds and their adjacent zones. The reason for this abundance is not because of chance but is due mainly to the need to simulate the joint geometry and its attendant components of a particular practical application using a suitable welding process and appropriate welding conditions and technique. A few tests have been designed primarily for use as research tools.

The main purpose of this paper is to 'bring to the notice' of its readers the different types of test that have been developed, to discuss the merits and demerits of some of them now being used, and to suggest in what way they are suitable for evaluating cracking tendencies.

For convenience, the details of the tests are contained in an Appendix, which can be read independently of the main text. A full list of the tests is summarized in Table I.

Nature of Cracking

Two main types of cracking, namely "hot" (supersolidus) and "cold" (sub-solidus) are known to occur. The chief variety, weld hot cracks, are thought to occur during the last stages of freezing and are due to the persistence of liquid films at grain boundaries in a harmful distribution over a relatively wide temperature interval.* Hot cracking in the heat-affected zone (H.A.Z.) is undoubtedly due to similar reasons but the mechanism by which liquid is encouraged to form is very different from that of the weld, and is not yet clearly understood. The weld cracking tendency is largely dependent on the freezing conditions in the molten pool, whereas the tendency for cracks to form in the H.A.Z. is greatly affected by the prior thermal and mechanical history of the material. One important observation is that if the solidus of the weld is lower than that of the base material then H.A.Z. cracks are unlikely to form. The reason for this is that until the weld gains some coherency it is unable to impose any strains on the adjacent zones. All hot cracks are intergranular.

Cold cracking, as the name implies, occurs at relatively low temperatures, and in steels (other than stainless steels) it is attributed to the occurrence of the austenite–martensite transformation and some form of internal stress *in the presence of hydrogen*. By implication, cracking occurs below the Ms temperature. In steels, weld and H.A.Z. (underbead or hard-zone) cracks are very similar and differ mainly only in distribution, size, and numbers. Whether or not cracking can occur in the absence of hydrogen is probably an academic point, but presumably it can if sufficient strains (stresses) are developed. Logically cracking will depend mainly on three factors:

(i) Presence of hydrogen
(ii) Degree of restraint
(iii) Type of microstructure.

The following suppositions would not appear to be unreasonable:

(*a*) In the absence of hydrogen, cracking will occur provided that a martensitic structure is developed and the degree of restraint is very high
(*b*) In the presence of a small amount of hydrogen cracking will occur when a martensitic structure is developed, and the restraint is only small. With increase in restraint cracking will occur in one of the other austenitic transformation products.

The cooling rate is probably important, not so much in itself, but in the way that it affects the type of microstructure developed, and the diffusion of hydrogen.

Underbead cracking is usually caused by the migration of hydrogen from the molten pool to the H.A.Z. If an austenitic electrode is used the tendency for underbead cracking is very much reduced or is eliminated; this is due mainly to the power of austenite in retaining large amounts of hydrogen in solution.

Factors Influencing Cracking

The main factors causing cracking are physical and metallurgical. The physical factors include type, size, and thickness of material, joint design, and size and shape of the weld bead, electrode type, coating and

* J. C. Borland: *Brit. Welding J.*, 1960, vol. 7 pp. 508–512.

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Table I

Summary of cracking tests

Test No.*	*Name of Test*	*Material Mainly Used*	*Welding Process*
Underbead (heat-affected zone) tests			
1.	Longitudinal Bead Weld	Steel	Metal-arc
2.	Circular Bead Weld	,,	,,
3.	Reeve Fillet Weld	,,	,,
4.	Reeve Butt Weld	,,	,,
5.	Controlled Thermal Severity (C.T.S.)	,,	,,
6.	BS.2549 Cold Cracking Test	,,	,,
7.	Cruciform	,,	,,
8.	B.W.R.A. Austenitic Steel	Cr–Ni austenitic steel	,,
Weld metal cracking tests			
Group A			
9.	Pad	Cr–Ni austenitic steel	Metal-arc
10.	X	,,	,,
11.	Cylinder	Steel	,,
12.	Single-T	,,	,,
13.	British Standard Single-T	,,	,,
14.	Double-T	,,	,,
15.	Hinds Specimen	,,	,,
16.	Butt Weld Restraint (Navy Torture Test)	Steels (various)	,,
17.	Lehigh Restraint	,,	,,
18.	Naval Research Laboratory Specimen	,,	,,
19.	B.W.R.A. Butt Weld Slotted Plate	Aluminium	,,
20.	Circular Patch	Steel	,,
21.	Navy Type Circular Patch	,,	,,
22.	Circular Groove	High-alloy steel	,,
23.	Segmented Groove	,,	,,
24.	Finger	,,	Metal-arc and tungsten-arc
25.	Cast Iron Block	Cast Irons	Various
26.	FISCO	,,	Metal-arc
Group B			
27.	Boudreau	Various	Tungsten-arc
Group C			
28.	Houldcroft Fishbone	Aluminium and steels	,,
29.	Murex Hot Crack Machine	Steels	Metal-arc
30.	Prokhorov Machine	,,	,,

* Also refers to number in the Appendix and Bibliography

size, heat input and cooling rate, current, arc voltage and arc length. The metallurgical factors have been discussed previously.

Plate size and thickness

Thick plates afford greater restraint than thin ones and thus can cause a greater amount of strain on the deposited weld bead which can lead to cracking. In addition, cooling rate usually increases with increased plate size and thickness and thus this factor can also increase cracking, particularly in steels. Thick plates are usually less worked and less homogeneous in composition than thin plates, and where zones of segregation occur cracks may form.

Joint design and bead shape

Joint design, besides affecting cooling rate and dilution effects, has a strong influence on whether or not regions of high stress concentration occur in a weld. During cooling for instance, a concave weld is subject to stress concentration on the thinnest and hottest section. A convex weld on the other hand has a thicker mid-section which cools last, and is less prone to cracking. Cracking in the heat-affected zone can be caused by the points of high stress concentration existing at the edge of convex welds. This applies to cold cracking during welding and cracking occurring during heat-treatment or service, rather than to hot cracking.

Backing bars are sometimes harmful, for they create a notch effect at the interface between the base plate and the backup.

Electrode type, coating and size

The effect of electrode type, coating, and size on cracking is linked with electrode 'suitability' and 'useability'. The type of coating affects the stabilization of the arc, controls the melting rate of the electrode and penetration power, and influences the shielding efficiency given to the weld so formed. The type of slag produced is very important, for it influences the shape of the bead and affects the kinetics of the slag/weld-metal reaction. The size of the electrode determines the current to be used and controls the size of the molten pool. Large electrodes, for instance, can cause cracking in austenitic weld deposits because the large molten pools when freezing cause excessive shrinkage. Several investigators have found that excessive slag causes concave weld bead deposits which are then susceptible to cracking.

Heat input and cooling rate

These factors are related to the welding speed and current. Low currents and high welding speeds give high cooling rates.

In the tungsten-arc welding of sheet, an increase in the current or speed or both can increase, decrease, or not affect the cracking tendency of welds. In some cases it first increases and then decreases the cracking tendency. As one would suppose, the reasons for the effect of these welding variables are not clearly understood. However, an increase in speed or decrease in current should steepen the thermal gradients existing in the base material and thus decrease the total contraction imposed on the weld. This should decrease cracking. On the other hand, an increased cooling rate should cause a further departure from equilibrium freezing conditions, and according to the composition of the material, could *increase* or *decrease* cracking.

Essential Features of a Cracking Test

An ideal cracking test should be:

(*a*) Cheap and simple to make
(*b*) Economical in material, labour, and time to conduct the test
(*c*) Able to show a direct correlation with fabrication requirements and service behaviour
(*d*) Simple to conduct
(*e*) Free from variations due to the human element
(*f*) Capable of giving reproducible results
(*g*) Able to show a high sensitivity to small changes in a test variable
(*h*) Able to show the effects of all welding variables
(*i*) Applicable to all welding processes.

Such a test has never been devised, of course, and is

not likely to be because of the very many different conditions found in practice.

The main consideration in choosing a suitable cracking test is that it should simulate the joint geometry of the practical application and show a direct correlation with the fabricator's requirements, and also service behaviour where this is important. It is common, however, and expedient, to choose, or to devise a test which imposes conditions that are more severe than those that would be normally experienced. Because of this it is not always possible to select a single test which can assess the cracking tendencies of both the weld and the heat-affected zone, particularly when it is desired to impose a maximum restraint on both zones and at the same time to evaluate a particular weld and base metal combination.

In Table I, which gives a summary of the tests, the various types of test are divided into two main sections; those normally used for assessing underbead cracking tendencies, and those used for weld-metal studies. The weld cracking tests have been divided into three groups. This classification is quite arbitrary and the reasons for doing it will be quite obvious.

Cracking Tests

Tests for assessing underbead cracking in steels (other than stainless steel)

The two most simple tests are the longitudinal and circular bead specimens, which involve the deposition of a single bead on a flat plate. Several tests must be conducted, however, to gain a reasonable result. With these tests the effects of external stress are at a minimum and thus the restraint factor is not studied. Whilst it is admitted that restraint may be only of minor importance in the formation of cold cracks in many steels, this may not be so in all steels, and thus these tests may have only a limited application. A further point is that external restraint, when present, assists in enlarging cracks, thus making them much more observable, where otherwise they might not have been seen. The drastic water quench imposed on the circular bead specimen does not simulate the uninterrupted thermal cycle experienced in normal welding and this could give rise to misleading results.

The Reeve fillet weld test, which was used extensively several years ago, incorporates maximum restraint combined with fast rates of cooling, and it is generally accepted that a steel which passes this test will be weldable in the vast majority of cases. However the test may classify many steels as unweldable, whereas some of them may be quite weldable in certain applications. If restraint is only a secondary, but nevertheless important agent, in making cracks observable, then it would be more logical to develop a test that would allow the effect of cooling rate to be studied, but at the same time incorporating sufficient restraint to assist in enlarging cracks which otherwise might be difficult to detect. The Controlled Thermal Severity (C.T.S.) test (which is a modification of the Reeve test) developed by Cottrell at the B.W.R.A. goes a long way in achieving this objective. In one of its forms it has been adopted as a British Standard cold cracking test for medium high-tensile steels. A disadvantage of the test, and this may apply only to certain steels, is that the effect of external restraint on cracking is not analysed. However, different degrees of restraint can be imposed on the heat-affected zone by using electrodes of different strength. High-strength austenitic electrodes cannot be used, because of the high solubility of hydrogen in austenite. It is assumed, of course, that the main source of hydrogen in the H.A.Z. is the molten pool.

The cruciform test has also been used to study underbead cracking in steels and it is claimed to be more severe than the C.T.S. test. Use of the cruciform test has made some investigators think that restraint is a very important factor in affecting cracking. It has been pointed out, however, that with this test hydrogen can migrate from one H.A.Z. to another, thus increasing the hydrogen content of the later weld joints, and thus the severity of cracking. The nature of the test should, however, impose more restraint than the C.T.S. test.

Chromium-nickel austenitic steel test for studying heat-affected zone cracking

This test has been recently developed by Borland and Younger at the B.W.R.A. The dimensions of the test are not yet finalized but, in its present form, it is proving most useful for studying the mechanism of base-metal cracking in austenitic steels during welding and under simulated service conditions. There are good reasons for believing that the test will give an indication of the performance of materials in power stations.

Initial studies with 18%Cr–13%Ni–1%Nb material, welded with a controlled ferrite electrode, showed that small hot cracks (about 0·030 in. deep) developed adjacent to the fusion zone. After heat-treatment at 750°C. these small cracks were found to have propagated, sometimes as much as 0·5 in. below the surface. If the initial hot cracks were removed by grinding, cracks were not initiated during the heat-treatment period. Cracking was not so severe when a lower strength electrode was used. With a type 316 (0·55%C) material hot tears produced during the welding cycle were not propagated under similar conditions of temperature and stress.

Further studies by Younger and Baker have shown that the microstructure, as observed under the electron microscope, is the most important factor influencing the propagation of the cracks during heat-treatment. Also if a very high strength electrode, which does not produce hot cracks because of its low solidus, is used cracks are initiated during the heat-treatment cycle with 18%Cr–13%Ni–1%Nb material but not with the type 316. It was concluded that cracking during reheating was always accompanied by the formation of a fine precipitate within the grains of the heat-affected zone. (This was absent in the type 316 material.) An increase in the strength of the weld metal resulted in more extensive cracking because of the greater strains produced in the heat-affected zone.

These authors also studied Nb- and Ti-stabilized and unstabilized 18% Cr–8% Ni steel and an 18% Cr–10% Ni Mo-stabilized steel. The primary use of the test is on a crack/no-crack basis.

Weld metal tests

The most simple and easy tests to perform are the pad, X type and cylinder specimen tests. The pad test,

which offers a minimum restraint as the weld metal is not confined by parent material, is the less severe of the three. The X test affords slightly more restraint because of the two square bars which form a weld joint. In addition, each succeeding test weld (4 in all) is deposited under more restraint. The specimen is primarily a 'go/no-go' cracking test, the cracking tendency being judged by noting in what run cracks first appear. In the cylinder test, only one test weld is deposited, but this is probably made under more restraint than the fourth test weld of the X test, as the test weld is deposited while the underneath restraining welds are still cooling down. The crack length is measured afterwards.

The single-T test is like the X test and relies on restraint produced by a cooling restraining deposit. However, the fillet joint formed by the abutting plates more closely resembles a practical joint configuration. Also the larger size of the plates affords a greater heat sink than is obtained with the X test. The British Standard (BS.639:1952) single-T test for mild steel is one form of the single-T test. For medium high-tensile steels, the British Standard test (BS.2549:1954) is slightly more severe, greater severity being obtained by using an austenitic electrode for depositing the restraining run.

The double-T test is a further development of the single-T test; however, here the welds are usually made singly, and each weld is deposited under more restraint than the previous one. It is claimed that the severity of the test may be further increased by cooling the specimen to the original temperature between welds.

The Hind's test is also a development of the single-T test. Here the two welds are deposited nearly simultaneously. Additional restraint is gained by increasing the width of the top member, and also by using an austenitic electrode for the restraining weld.

When welds are to be made in thicker material it is necessary to use larger test specimens which more closely simulate the practical application. Thus for butt welds the Navy Torture test or other similar tests are very useful. These types of test usually simulate the most severe conditions that are likely to be met in practice.

Another test, which is widely used in America, is the Lehigh Restraint specimen and its many modifications. With this test an effort is made to determine the degree of restraint that is necessary to produce cracking. Different degrees of restraint are obtained by cutting slots of various depths into the sides of a rectangular plate which is securely clamped in a welding jig. This is a 'go/no-go' test and several specimens must be welded to gain a result. A test that was designed to overcome the need for preparing several samples is the Naval Research Laboratory specimen. This, however, has not been used with much success. Another test, not unlike the N.R.L. test, is the B.W.R.A. slotted plate specimen. The degree of restraint is altered by the length of the slot. Several specimens are necessary to gain a result, the cracking index being the minimum slot length at which crack-free welds are produced.

Where patches have to be welded, or circular welds made, the circular patch or circular groove tests are more applicable. With these types of test the restraint is usually greater than in butt welds of similar dimensions. The degree of restraint may be varied by altering the size of the patch; the smaller the patch the greater is the restraint.

In practical applications where weld-metal cracks may be caused by 'notches' or 'interfaces' the finger and segmented groove tests should be useful.

There are only a few cracking tests for use with tungsten-arc welding; of these the Houldcroft Fishbone test appears to be the most promising. The principle underlying the development of this test is different from the others, for the test measures the ease with which a propagating crack is stopped. For this reason it can be used only for comparative purposes, and as the mechanism of the test has not yet been fully elucidated it is not possible yet to assume that a close relationship between crack length and weldability exists as has been assumed to apply in other tests.

Discussion

It must be emphasized that the main consideration in choosing a suitable cracking test is that it should simulate as closely as possible the joint geometry of the practical application and should show a satisfactory degree of correlation with its weldability. Where behaviour of the welded joint in service is important, the test should be capable of providing information which will allow this aspect to be evaluated. If the whole test specimen cannot itself be subjected to the appropriate tests, then it should be capable of supplying test specimens. For weld-metal evaluation, a simple tensile test can provide useful basic information, *i.e.*, yield strength (or proof stress), tensile strength, ductility, and hardness. The ratio hardness/tensile strength (H_D/T) will also afford an indication of the notch impact strength, if the relationship between the ratio and impact strength is known previously. (For many steels this relationship is almost linear over a wide range.) In general, as this ratio increases, the impact strength decreases.

Cracking tests appear to be of two main types:

Class A (crack/no-crack type)
(i) Single test specimen
(ii) Several test specimens

Class B (tests when cracking tendency is assessed by measurements of crack length)
(i) Restraint factor constant*
(ii) Restraint factor continuously varied in single specimen.

The class B(ii) test is, in fact, a special form of the class A(ii) type of test. This is because, as the restraint is reduced along the specimen, a stage is reached where the crack cannot propagate further; this is a crack/no-crack position. However, unlike the class A(ii) type, test, the index of cracking is based on the ease with which the propagating crack is stopped. The class A(ii) type test, of course, measures the ease of starting a crack.

In some cases class A tests are also used as class B(i) tests. This is because of the need sometimes to discriminate between class A tests which have cracked.

The type of specimen which should best reflect 'weldability' in practice is the crack/no-crack test.

* There is no reason why specimens which are usually used as this type of test, should not also be used as Class A(i) tests.

Tests which give a measurement of crack length are best suited to those establishments where basic research is being conducted. A recent note to the *Journal** and other work† implies that crack length is related to the extent of the freezing range (this is related to the brittle range or critical solidification range)—at least for solid-solution alloys. It would not appear to be logical to relate the extent of the freezing range to 'weldability', for the freezing range is an inherent property of the alloy and cannot be altered to any large extent by variation in welding techniques.

For assessing the underbead cracking tendency in steels, the C.T.S. test would appear to be the most valuable test yet devised. If restraint is an important contributory factor causing cracking, then this aspect can to some extent be evaluated by using high-strength electrodes, although these may tend to cause weld-metal cracking. This will lessen the restraint imposed on the heat-affected zone. A more severe test is the Reeve test.

Heat-affected-zone cracking in Cr–Ni austenitic steels can be assessed with the B.W.R.A. austenitic steel base-metal cracking test. This appears to be the only test devised to study this problem. Different degrees of restraint can be imposed by using electrodes of various strengths. The electrode used need not be austenitic. The severity of the test could also be altered by varying the ratio of stub-pipe-dia./external-block-dimension.

There are several weld-metal cracking tests that are very useful, the type selected depending on the practical application in mind. Of the tests in group A (Table I), the pad, X, cylinder, Hinds,‡ and Naval Research Laboratory tests do not appear to have special merit that would necessitate their use. The pad and X tests might however be useful where simple joints with little or no restraint are involved.

The Lehigh Restraint, B.W.R.A. slotted plate, and finger tests (class A(ii)) appear to offer the best assessment of cracking tendencies, because of the various degrees of restraint that can be imposed. The circular patch, and circular groove tests could also be made more useful by varying the patch-(groove)-dia./external-block-dimension ratio to give various degrees of severity, and using them as class A(ii) tests.

In group B the Boudreau test does not appear to offer any advantage over others, and furthermore the cracking index assigned does not appear to be directly related to 'weldability'.

In group C the Murex hot-crack machine provides an extremely severe test of weld metal. It can be used, however, only as a comparative test. It should be extremely useful for assessing electrodes of a type where a sound knowledge has been gained previously on the relationship between the Murex crack length and weldability in practice *for similar electrodes*.

The Houldcroft fishbone test is a rather special form of the principle underlying the mechanism of the Murex hot-crack machine. In its present form, however, the test could conceivably give inconsistent results because of its smallness. The variation in severity along the specimen is obtained by slotting the plate to various depths (Fig. 23*a*). These slots act to alter the strains on the weld pool by changing the thermal strains created by the heat flow distribution. This in itself is a good arrangement; unfortunately the thermal distribution will also be disturbed by the starting edge and end of the specimen. Small variations in welding speed could thus have a large effect on the size of the thermal strains created. A quasi-stationary heat-flow pattern will not be obtained (even for a constant bead width) unless the arc is several melted widths from the edges of the specimen. An improvement to the test might be to add on to the two ends a 'head' and a 'tail' so that the quasi-stationary state of heat flow is achieved by the time the arc has reached the first slot. Also this arrangement might increase the sensitivity of the specimen at both end regions of the slotted portion.

As with the Murex test, the Houldcroft specimen is a comparative test, and should be useful for evaluating similar materials.

* J. C. BORLAND: *Brit. Welding J.*, 1960, vol. 7, pp. 558–559.

† W. I. PUMPHREY and P. H. JENNINGS: *J. Inst. Metals*, 1948, vol. 75, pp. 235–256.

‡ However, the severity of the test can be increased by altering the width of the top member.

Bibliography

GENERAL REFERENCES

R. D. STOUT and W. D. DOTY: 'Weldability of Steels', Welding Research Council, 1953.

A. J. WILLIAMS, P. J. RIEPPEL, C. B. VOLDRICH: "Literature Survey on Weld Metal Cracking", 1952, W.A.D.C. Tech. Report 52–143.

SELECTED REFERENCES

Underbead (Heat-affected zone) tests

(1) *Longitudinal Bead Weld*

G. G. LUTHER, F. H. LAXAR, C. E. JACKSON: *Welding J.*, 1945, vol. 24, pp. 245*s*–254*s*.

C. B. VOLDRICH: *Welding J.*, 1947, vol. 26, pp. 153*s*–169*s*.

C. E. SIMS and H. M. BANTA: *Welding J.*, 1949, vol. 28, pp. 178*s*–192*s*.

M. W. MALLETT and P. J. RIEPPEL: *Welding J.*, 1946, vol. 25, pp. 748*s*–759*s*.

(2) *Circular Bead Weld*

S. L. HOYT, C. E. SIMS, H. M. BANTA: *Welding J.*, 1945, vol. 24, pp. 433*s*–445*s*.

C. B. VOLDRICH and R. D. WILLIAMS: *Welding J.*, 1943, vol. 22, pp. 545*s*–554*s*.

(3) and (4) *Reeve Fillet Weld and Butt Weld*

T. SWINDEN and L. REEVE: *Trans. Inst. Welding*, 1938, vol. 1 pp. 7–24.

J. G. BALL: *Trans. Inst. Welding*, 1943, vol. 6, pp. 24–46.

J. DEARDEN and H. O'NEILL: *Trans. Inst. Welding*, 1940, vol. 3, pp. 203–214.

C. L. M. COTTRELL and P. H. R. LANE: *Trans. Inst. Welding*, 1952, vol. 15, pp. 2*r*–12*r*.

(5) *C.T.S. Test*

C. L. M. COTTRELL, M. D. JACKSON, J. G. PURCHAS: *Trans. Inst. Welding*, 1952, vol. 15, pp. 50*r*–57*r*.

C. L. M. COTTRELL: *Welding J.*, 1953, vol. 33, pp. 257*s*–272*s*.

Commission IX, I.I.W.: *Brit. Welding J.*, 1959, vol. 6, pp. 354–361.

(6) *British Standard Cold Cracking Test*

BS.2549:1954, Appendix E.

(7) *Cruciform*

L. REEVE: Document R 11/88, Inst. Welding, 1942.

J. G. BALL: *Trans. Inst. Welding*, 1943, vol. 6, pp. 24–46.

L. E. POTEAT and W. L. WARNER: *Welding J.*, 1960, vol. 39, pp. 70*s*–76*s*.

K. WINTERTON and M. J. NOLAN: *Welding J.*, 1960, vol. 39, pp. 77*s*–82*s*.

(8) *B.W.R.A. Austenitic Test*

R. N. YOUNGER and J. C. BORLAND: Confidential Report No. B5/3/59, Brit. Welding Res. Assn.

R. N. YOUNGER and R. G. BAKER: Confidential Report No. B5/6/60, Brit. Welding Res. Assn.

Weld Metal Cracking Tests

Group A

(9) *Pad Test*

E. C. ROLLASON and M. C. T. BYSTRAM: *J. Iron Steel Inst.*, 1951, vol. 169, pp. 347–352.

(10) X *Test*

T. E. KIHLGREN and C. E. LACY: *Welding J.*, 1946, vol. 25, pp. 769*s*–775*s*.

(11) *Cylinder*

P. WERTHEBACH: *Stahl u Eisen*, 1953, vol. 73, pp. 84–91. (Abstracted in *Welding J.*, 1953, vol. 33, p. 302*s*.)

(12) *Single-T*

(13) *British Standard Single-T*

BS.639:1952, Appendix D. (Mild steel.)

BS.2549:1954, Appendix D. (Medium high-tensile structural steel.)

(14) *Double-T Joint*

S. A. HERRES: *Trans. Amer. Soc. Met.*, 1947, vol. 39, pp. 162–192.

S. A. HERRES and P. E. WOODWARD: *Welding J.*, 1946, vol. 25, pp. 646*s*–658*s*.

K. WINTERTON and E. G. P. HINDS: *Brit. Welding J.*, 1955, vol. 2, pp. 513–525.

(15) *Hinds Specimen*

E. G. P. HINDS: *Trans. Inst. Welding*, 1952, vol. 15, pp. 27*r*–28*r*.

(16) *Navy 'Torture' Test*

U.S. Navy Dept., Specification 46E4.

R. D. STOUT and W. D. DOTY: "Weldability of Steels", p. 237–238, Welding Research Council, 1953.

(17) *Lehigh Restraint Test*

R. D. STOUT, S. S. TOR, L. J. MCGEADY, G. E. DOAN: *Welding J.*, 1946, vol. 25, pp. 522*s*–531*s*.

R. D. STOUT, S. S. TOR, L. J. MCGEADY, G. E. DOAN: *Welding J.*, 1947, vol. 26, pp. 673*s*–682*s*.

R. P. SOPHER, A. J. JACOBS, and P. J. RIEPPEL: *Welding J.*, 1955, vol. 34, pp. 544*s*–552*s*.

(18) *Naval Research Lab. Test*

G. G. LUTHER, C. E. JACKSON, C. E. HARTBOWER: *Welding J.*, 1946, vol. 25, pp. 376*s*–396*s*.

(19) *B.W.R.A. Butt Weld Slotted Plate*

W. G. HULL, D. F. ADAMS, H. E. DIXON: *Brit. Welding J.*, 1955, vol. 2, pp. 32–37.

(20) *Circular Patch*

H. F. TREMLETT: *Welding*, 1944, vol. 12, pp. 440–445, 493–500.

P. L. J. LEDER: *Proc. Inst. Mech. Eng.*, 1948, vol. 159, pp. 173–190.

(21) *Navy Circular Patch*

U.S. Military Specification MIL-E-986 (Ships).

R. D. STOUT and W. D. DOTY: "Weldability of Steels", pp. 236–237, Welding Research Council, 1953.

W. H. WOODING: *Welding J.*, 1950, vol. 29, pp. 552*s*–564*s*.

(22) *Circular Groove*

A. W. STEINBERGER, B. J. DESIMONE, J. STOOP: *Welding J.*, 1950, vol. 29, pp. 752–764.

(23) *Segmented Groove*

A. J. WILLIAMS, R. D. WILLIAMS, C. B. VOLDRICH: Summary Report. Battelle Memorial Inst., March 1949.

A. HOERL and T. J. MOORE: *Welding J.*, 1957, vol. 36, pp. 442*s*–448*s*.

(24) *Finger Test*

W. R. APBLETT and W. S. PELLINI: *Welding J.*, 1954, vol. 33, pp. 83*s*–90*s*.

P. P. PUZAK, W. R. APBLETT, W. S. PELLINI: *Welding J.*, 1956, vol. 35, pp. 9*s*–17*s*.

(25) *Cast Iron Block*

W. A. SCHUMBACKER and A. L. SCHAEFFLER: *Welding J.*, 1956, vol. 35, pp. 91*s*–99*s*.

G. R. PEASE: *Welding J.*, 1960, vol. 39, pp. 1*s*–9*s*.

(26) *FISCO*

H. M. SCHNADT: *Oerlikon Schweissmitteilungen*, 1957, vol. 15, pp. 31–42.

Group B

(27) *Boudreau Sheet Test*

J. S. BOUDREAU: *Welding J.*, 1956, vol. 35, pp. 164*s*–168*s*.

E. H. KINELSKI and G. R. PEASE: *Welding J.*, 1956, vol. 35, pp. 498*s*–500*s*.

Group C

(28) *Houldcroft Fishbone Test*

P. T. HOULDCROFT: *Brit. Welding J.*, 1955, vol. 2, pp. 471–475.

F. J. WILKINSON, C. L. M. COTTRELL, and H. V. HUXLEY: *Brit. Welding J.*, 1958, vol. 5, pp. 557–562; 1959, vol. 6, pp. 312–314.

(29) *Murex Hot Cracking Machine*

H. MARTIN: *Welder*, 1940, vol. 12, pp. 140–141.

E. C. ROLLASON: *Welder*, 1953, vol. 22, pp. 45–53.

P. W. JONES: *Brit. Welding J.*, 1957, vol. 4, pp. 189–197.

P. W. JONES: *Brit. Welding J.*, 1959, vol. 6, pp. 282–290.

E. C. ROLLASON and D. F. T. ROBERTS: *Brit. Welding J.*, 1954, vol. 1, pp. 441–447.

(30) *Prokhorov Machine*

N. N. PROKHOROV: *Svarochnoe Proizvodstvo*, 1956, No. 6, pp. 5–11.

APPENDIX

Underbead and Heat-affected Zone Cracking Tests

(1) Longitudinal Bead Weld Underbead Cracking Test

This simple test consists of a block of steel 2 in. wide by 3 in. long (in the direction of rolling) by the full thickness of plate under investigation (Fig. 1).

A bead 1½ in. long is deposited with a ⅛ in. dia. E6010 type electrode at a current of 100 amp. and 24–26 arc volts and a travel speed of 10 in./min. The block is pre-cooled or pre-heated to one of several temperatures, and during welding and for one minute afterwards is immersed to within ¼ in. of its top surface in a liquid bath at the chosen temperature. It is then removed and held for 24 hr at 15°C. and is then tempered for 1 hr at 595°C.

The cracking tendency is assessed from a longitudinal microsection by magnetic particle or metallographic techniques, and the total length of crack(s) is expressed as a percentage of the bead length. For a reasonable evaluation ten tests have to be conducted.

(2) Circular Bead Weld Underbead Cracking Test

This test was primarilly developed for sheet steel ½ in. thick. For the test, a specimen ½ in.×2 in.×2 in. is sandwiched between copper cooling plates with suitable openings, as shown in Fig. 2. A circular bead weld about 1 in. in diameter is deposited with a ⅝ in. dia. E6013 electrode at 50–55 amp., 24–26 arc volts, and a welding speed of about 9½ in./min.

Immediately after welding the specimen is quenched in iced water to induce cracking, and is then held at room temperature for 24 hr and afterwards stress-relieved for 1 hr at 565°C.

The extent of cracking is expressed (after grinding the surface flush) as a percentage of the maximum crack length possible, or 720 degrees, since cracking can occur on both the inside and outside periphery of the weld. Six specimens are usually required for each steel tested.

Reeve Tests

The Reeve tests were designed primarily for determining the tendency of a steel to crack either during or immediately after welding. Weld cracking is also assessed.

(3) Fillet Test

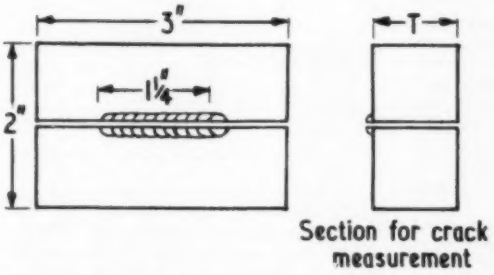
This test consists of depositing a fillet weld between one side of a square plate and a rectangular plate placed underneath. Anchor welds are made previously on the other three sides of the square plates and the whole assembly is bolted to a 2¼ in. thick mild steel base plate. When the anchor welds are completed, the whole specimen is cooled to near room temperature and the bolts are retightened before making the test weld.

The dimensions of the specimen vary with the thickness of plate under test. Figure 3 shows the form of the test for 1 in. thick material.

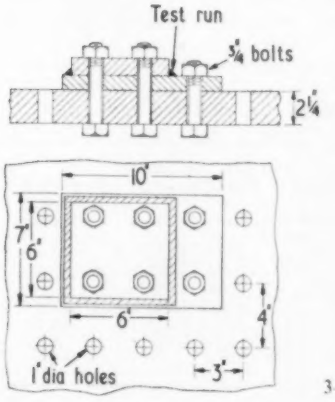
Metallographic samples ½–⅝ in. long are taken from the mid-section of the test weld and examined for cracking tendencies. Hardness surveys are also usually made.

(i) *Dearden and O'Neill Modification*

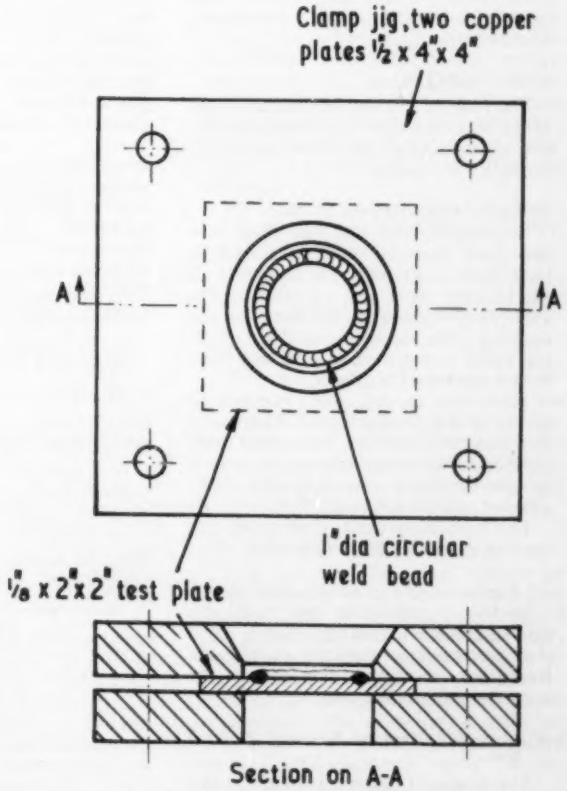
In this arrangement two test fillets are made instead of one. To do this the bottom test plate is extended to 13 in.



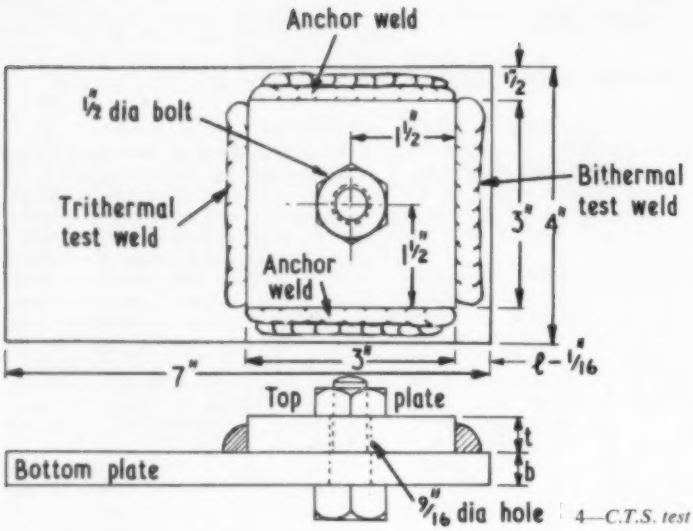
1—*Longitudinal bead weld cracking specimen*



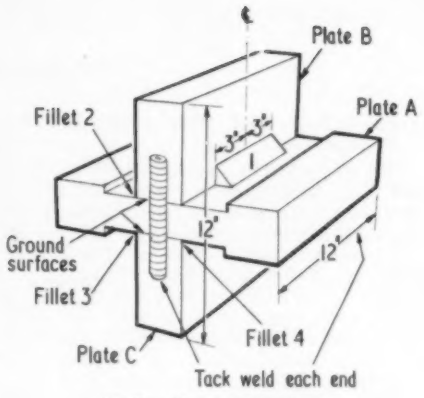
3—*Reeve fillet weld cracking test*



2—*Circular bead weld underbead cracking test*



4—*C.T.S. test assembly for alloy steels*



5—*Cruciform test specimen*

and the second fillet is made in the position of the back anchor weld.

(ii) *Reeve modification for high-alloy steel*

For high-alloy steels, which are hard to drill, steel straps are placed over the plates and firmly bolted to the mild steel plate. The two side anchor welds are essential, otherwise very little restraint is obtained.

(4) Butt Weld Test

The form of this test, is similar to that of the fillet test (see Fig. 3) except that two upper square plates are needed to provide a butt joint.

(i) *Reeve Modifications*

To simplify the test and thus save time and material two modifications have been suggested: (*a*) Removal of the backing plate and omission of the anchoring welds; and (*b*) removal of the backing plate, omission of the anchoring welds and provision of a test plate with a machined V groove.

These two modifications are not so severe as the standard test. Whereas in the standard test the weld and heat-affected zones are liable to crack, usually in the modified tests only the heat-affected zones would suffer.

For high-alloy steels, steel straps are used as in the modified fillet test.

(ii) *Rollason and Cottrell Modification*

In this modification, the bolts, the side anchoring welds and heavy mild steel base plate are omitted. As with the Reeve modifications, this is not so severe as the original test.

(5) Controlled Thermal Severity (C.T.S.) Test

The design of this test is based on the assumption that the extent of 'hard-zone' cracking is mainly dependent on the cooling rate at about 300°C., as measured in the heat-affected zone adjacent to the fusion line. When a critical rate of cooling for a given electrode–steel combination is exceeded, cracking is supposed to occur irrespective of the external restraint applied.

The C.T.S. test comprises two plates, one square (top plate) and the other (bottom plate) almost twice as long, clamped together with a single bolt and two side anchor welds (Fig. 4). The two plate surfaces in contact are surface ground to obtain efficient heat flow.

After the test specimen has been assembled it is allowed to cool to room temperature before the bithermal test weld is deposited, and again before the trithermal weld is made. Various thermal severities are obtained by using different thicknesses of plate (Table A). The thermal severity number is obtained from the following formulae:

(*a*) TSN = 4 (*t* + *b*) for bithermal welds
(*b*) TSN = 4 (*t* + 2*b*) for trithermal welds.

The severity of cracking is determined by measurements of crack length on metallographic sections.

Table A

C.T.S. assemblies and thermal severity numbers (T.S.N.)

Plate thickness, in. Top	Bottom	*Heat Flow from Test Weld*	*T.S.N.*
Main Series			
¼	¼	Bithermal	2
		Trithermal	3
½	½	Bithermal	4
		Trithermal	6
1	1	Bithermal	8
		Trithermal	12
2	2	Bithermal	16
		Trithermal	24
Supplementary Series			
¼	½	Bithermal	3
		Trithermal	5
¼	1	Bithermal	5
		Trithermal	9

A weldability index (Table B) has been proposed and operates as follows. Fillet welds, each of ¼ in. leg length, are laid on assemblies of different thermal severity and examined for cracking. The steel is then given a weldability index letter, depending on which of the tests

Table B

Weldability Index

Critical Cooling Rate (at 300°C.) above which Hard-Zone Cracks occur °C./sec	*Hard-Zone Cracking in ¼ in. Leg Length Fillets on C.T.S. Assembly*		*Weldability Index Letter*
	Present with T.S.N.	*Absent with T.S.N.*	
Over 32	—	12 and under	A
20–32	12	8 and under	B
11–20	8 and over	6 and under	C
6–11	6 and over	4 and under	D
4–6	4 and over	3 and under	E
2–4	3 and over	2 and under	F
Under 2	2 and over	—	G

show cracking. The index is then completed by prefixing the coating group number of the electrode used for the tests.

(6) British Standard Cold Cracking Test for Medium High-tensile Structures (BS.2549:1954)

This is one form of the C.T.S. test (see Fig. 4). Only one weld, the tri-thermal weld, is tested however, and the thickness of the plates is standardized at $\frac{1}{2}$ in. The following is an extract from BS.2549:1954:

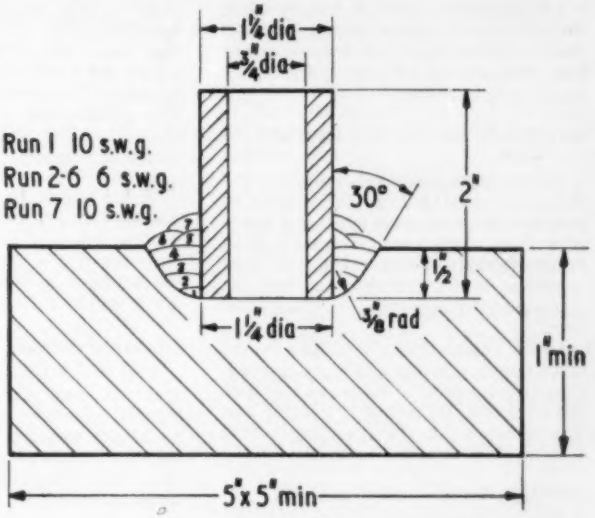
"Two plates, one 3 in. × 3 in. and the other 7 in. × 4 in., each of a thickness of $\frac{1}{2}$ in. (or 20 lb), shall be used for the test. The test weld edge of the top plate shall be finished by machining and, if gas cutting has been used in cutting out the plates, a minimum of $\frac{1}{4}$ in. shall be removed. The lower face of the top plate and the upper face of the bottom plate shall be machined flat. The thickness of each plate shall not be reduced below 0·460. The interface shall be free from millscale, oil and other foreign matter before the plates are bolted together.

"The plates should be drilled and tightly bolted together with a $\frac{1}{2}$ in. diameter bolt [as shown in Fig. 4]. Anchor welds shall then be deposited in the flat position round three sides of the top plate using a 6 s.w.g. electrode to give $\frac{3}{8}$ in. leg length fillet welds. Multi-run anchor welds may be used if the runs are deposited in quick succession. Visibly cracked anchor welds shall be replaced.

"Any slackness in the bolt shall be taken up immediately before the test weld is made. The temperature of the parent metal used for making test pieces shall be 10–30°C. (50–85°F.) immediately before depositing the test weld.

The test assembly shall be held so that the test weld is deposited in the flat position. If a jig is used for this purpose the metallic contact with the jig shall be such that the thermal severity of the test is not affected. The earth connection shall be attached to the head of the bolt and shall be removed immediately after the test weld is completed. The test weld shall be a uniform fillet* of $\frac{5}{16}$ in. leg length deposited with a 6 s.w.g. electrode using the approximate mean of the range of current recommended by the manufacturer. The test weld shall be 3 in. long.

"The test assembly shall be sectioned after a minimum time of 72 hours at room temperature (10–30°C.). The sections shall then be examined for cracks both in the weld metal and in the heat-affected zone of the plate."



6—*B.W.R.A. austenitic steel base-metal cracking test*

(7) Cruciform Test (see double-T joint)

This test is essentially a development of the double-T joint specimen used mainly for weld metal studies but its object is mainly to differentiate between various qualities of armour steel, which are susceptible to heat-affected zone cracking when making fillet joints. There is no reason why material other than armour plate should not be evaluated with this test. Dimensions of the test are given in Fig. 5.

For a complete assessment of armour steels, three plate thicknesses are usually used:

Plate thickness, in.	*Plate sizes, in.*
½	One plate (A) 12 × 12 × ½
	Two plates (B & C) 6 × 12 × ½
1	One plate (A) 8 × 12 × 1
	Two plates (B & C) 4 × 12 × 1
1½	One plate (A) 8 × 12 × 1½
	Two plates (B & C) 4 × 12 × 1½

Before the fillet welds are deposited, the whole specimen is 'tack' welded. During this assembly, jigs are used to obtain the accurate fit-up required. Each fillet (6 in. long) is welded in the down-hand position and is so placed as to extend 3 in. on each side of the mid-point of the length of the test specimen. If cracking in the weld occurs the test is declared void.

Before being examined for cracks the weld is allowed to stand for at least 48 hr, stress-relieved at 595°–650°C. for 2 hr, and then furnace cooled.

Cracking is assessed from metallographic samples. No cross-section for examination must be taken within 1 in. of either end of any fillet weld.

(8) B.W.R.A. Test for Cr–Ni Austenitic Steels

This test was developed for investigating the type of cracking found at welded joints between steam pipes and headers in Cr–Ni austenitic steels. The dimensions of the test are by no means standardized yet, as further work with the test is still progressing; a typical specimen found most useful is shown in Fig. 6.

Two types of crack are observed: (*a*) Hot cracks—these occur during welding and are extremely small (about 0·030 in. deep); and (*b*) cracks formed during heat-treatment—these usually start from initial hot tears and propagate sometimes to a distance of $\frac{1}{2}$ in. below the surface.

The forms of the heat-treatment cracks are very similar to those found in components in services.

Weld Metal Tests

(9) Pad Test

This very simple test involves depositing one or more (usually several) beads on a $\frac{1}{2}$ in. thick plate of the material to be welded. Cracking is assessed by micro-examination of suitable sections. It has been mainly used for assessing Cr–Ni austenitic weld metal.

(10) X Weld Cracking Test

This test has been used mainly to study cracking in nickel-chromium-iron weld deposits. It consists essentially of two 3-in. long pieces of 1-in. square bar, clamped with their edges together to form a double-V groove. Welding is done by depositing two passes at a time on alternate sides, allowing the specimen to cool below 40°C. between each pair of passes. The sequence using $\frac{5}{32}$ in. electrodes is shown in Fig. 7.

* "It is important that the electrode is deposited at a uniform rate. It will be helpful to the welder if the electrode is marked to indicate the estimated length of electrode required to be deposited to obtain the specified length and size of weld. A half-way mark on the estimated length of electrode, together with a chalk mark at the half-way distance on the test assembly, is also a useful guide to the welder."

Cracking is assessed by noting when the first cracks appear during welding. Should all the welds appear to be crack-free, sections are cut out and metallographically examined.

(11) Cylinder Specimens for Electrodes and Steels

The cylinder specimen comprises two bars, 2 in. long by 2 in. dia., welded together in three passes in rapid succession with $\frac{5}{32}$ in. electrodes, using the highest recommended current (Fig. 8). The specimen is then turned over and the test weld (4) is deposited on the reverse side.

Crack susceptibility is judged by the crack length, crater cracks being ignored. Cracking is stated to be moderate when the total crack(s) length is 1 in. or less, and severe when the cracking is over 1 in.

(12) Single-T Fillet Weld

This test consists of welding together two plates to form a single-T specimen (Fig. 9). The second run is made immediately after the completion of the first pass. The abutting portions are machine finished, for rough edges tend to reduce the restraint on the fillet welds. The dimensions of the test, size of electrodes, and welding conditions are varied to suit the particular application in mind.

Welds which do not crack in either run are rated "crack-free". The second weld is deposited under greater restraint than the first so that if the first pass cracks the weld metal is rated as highly crack sensitive.

(13) British Standard Single-T Tests

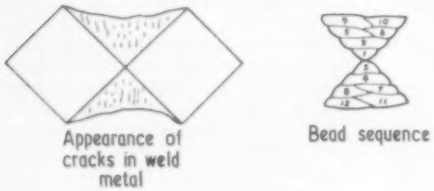
This is one form of the single-T test and has been adopted as a British Standard for covered electrodes for the metal-arc welding of mild steel and medium high-tensile structural steel (Fig. 10). For mild steel two test fillet welds each of $\frac{1}{4}$ in. leg length are made using 6 s.w.g. electrodes, whereas for medium high-tensile steels, the first weld is made using a 4 s.w.g. austenitic electrode.

The following is an extract from BS. 2549:1954 relating to medium high-tensile steel:

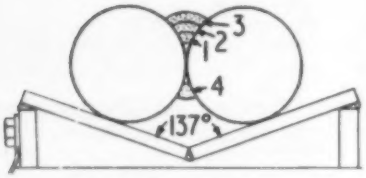
"The temperature of the parent metal used for making test pieces shall be 10–30°C. (50–85°F.) immediately before depositing the first run of weld metal.

"A 6 in. × 3 in. plate shall be welded to a second plate 6 in. × 6 in. in the form of a close square T-joint. The plates shall be $\frac{1}{2}$ in. thick (or 20 lb). The edge of the first plate abutting the surface of the second plate shall be prepared by machining or grinding, and the gap between the parts, after tack welding at the ends in preparation for welding, shall not exceed 0·10 in.

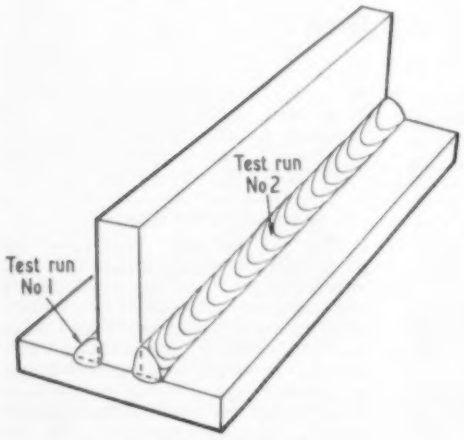
"A fillet weld 5 in. long and of $\frac{5}{16}$ in. leg length shall be deposited in the flat position on one side using a single 4 s.w.g. austenitic electrode. This austenitic electrode shall be of the type



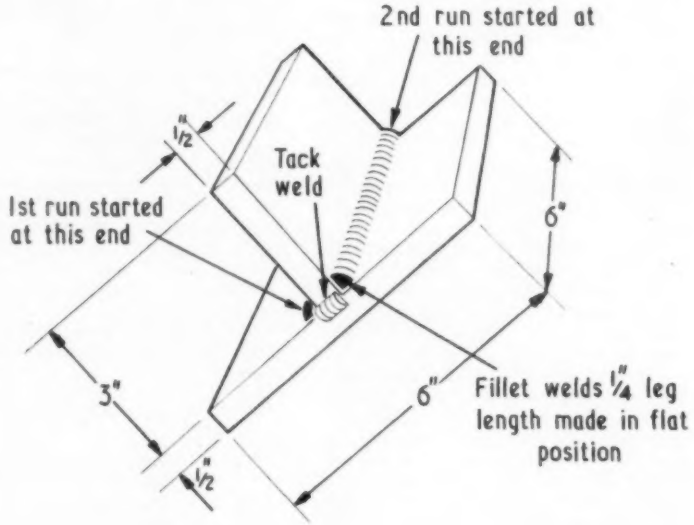
7—*X crack test specimen*



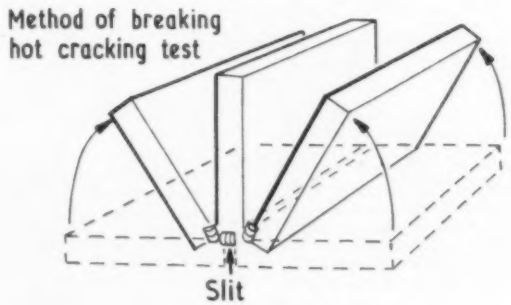
8—*Cylinder specimen*



9—*Single-T test specimen*



10—*British Standard single-T test specimen*



depositing steel containing approximately 18% chromium, 7% nickel and not less than 2% molybdenum. The test fillet weld 5 in. long and of $\frac{1}{4}$ in. leg length shall then be deposited in the flat position using a single 6 s.w.g. electrode. The maximum current of the range recommended by the manufacturer of the electrode shall be used. For each weld the test piece shall be so positioned that the slope and the rotation of the weld are zero. The test weld shall be started at the end of the test piece at which the austenitic weld finished and the time interval between completing the austenitic weld and commencing the test weld shall be four to five seconds.

"The slag shall be removed from the test weld after the test piece has cooled in still air to room temperature and the surface of the weld shall be examined visually for cracks.

"The second plate shall be slit and the welds broken open [as shown in Fig. 10.] The test weld shall then be examined for evidence of hot cracking as indicated by oxidation or temper colouring of the surfaces of the fractures."

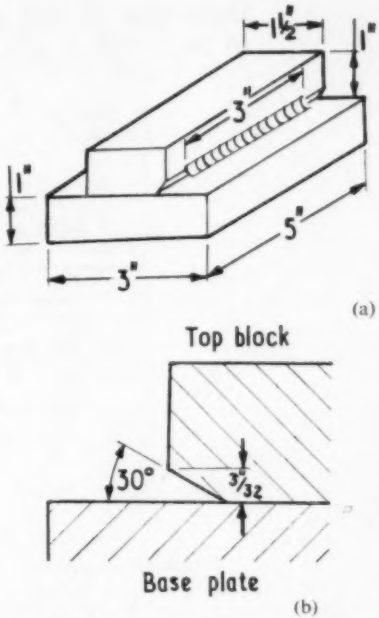
(14) Double-T Fillet Weld

This is another version of the Cruciform type test. The size of the test and welding conditions are varied as required. Four fillet welds are deposited, each weld being made under more restraint than the previous one (see Fig. 5). The severity of the test may be further increased by cooling the specimen to the original temperature between welds. As with the single-T test, machining of the appropriate faces and an accurate fit-up are essential for genuine and reproducable results. Besides noting in what fillets cracks are first observed, sections are taken and metallographically examined.

Since the restraint and cooling rates developed are higher than in the single-T tests, an examination when appropriate is also made for cracks in the heat-affected zone.

(15) Hinds Double Fillet Test

This test (Fig. 11) has been developed from the single-T test. In contrast to this test, however, the two welds, the restraining weld and the test weld, are laid nearly simultaneously. Other features of the Hinds test are that the width of the top member, which alters the severity of the test, is much greater than that of the single-T test, and also the restraining weld is made with an austenitic electrode (as in BS.2549:1954). This also increases the severity of the test owing to the greater coefficient of thermal contraction of the austenite. A fourth difference is that the underside of the top member is chamfered to prevent root penetration by the restraining weld. If this happens, unreliable results are obtained.



11—*Hinds specimen*: (a) *Showing restraining weld;* (b) *enlarged view of chamfered edge*

In conducting the test, both welds are made in the same direction, the test weld being laid in the left to right direction. The restraining weld is started 1 in. from the edge of the plate and the test weld $1\frac{3}{4}$ in. from the edge. The restraining weld is 3 in. long and the test weld $1\frac{1}{2}$ in. long.

The time interval between the start of the two welds is standardized as follows:

For 1 in. top member the time interval is 6 sec
For $1\frac{1}{2}$ in. top member the time interval is 5 sec
For 2 in. top member the time interval is 4 sec.

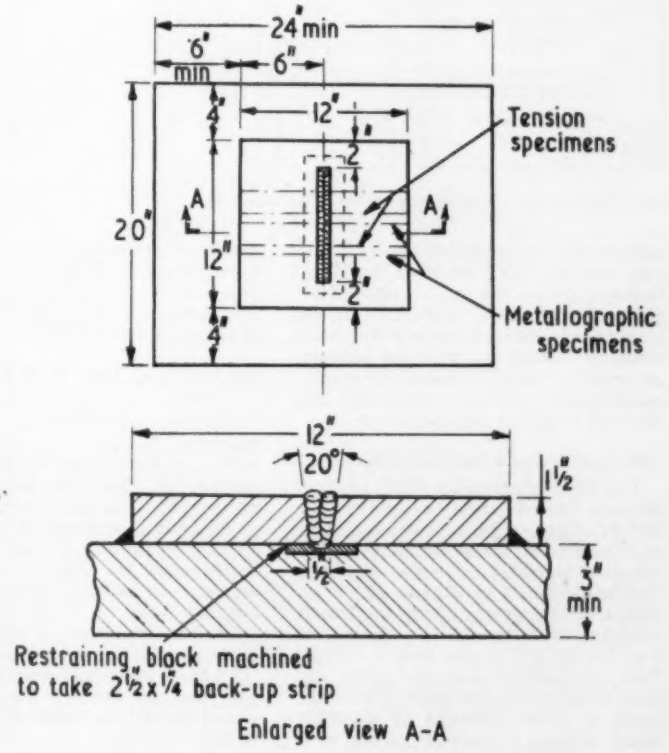
After completion of the test, the test weld is visually examined for cracking.

(16) Butt Weld Restraint Test

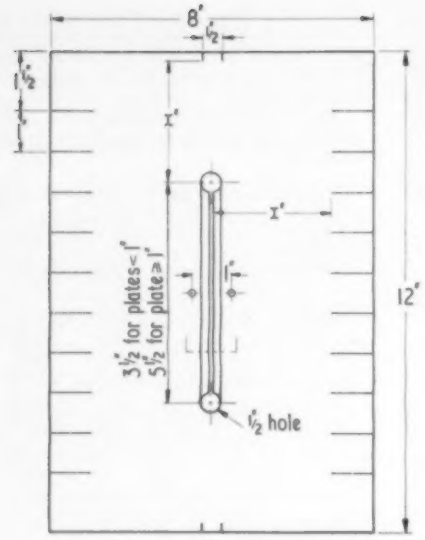
There are many types of this test. One version, the Navy Torture test, is shown in Fig. 12 and is used for the qualification of austenitic Cr–Ni stainless steel electrodes. This type of test is especially useful for assessing weld metal in thick plate.

(17) Lehigh Restraint Test

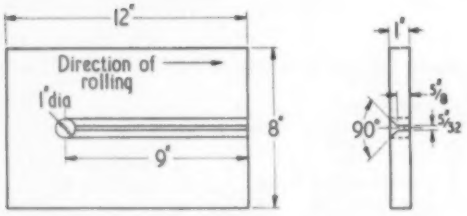
This test is used primarily to study the degree of restraint that is necessary to produce weld-metal cracking. The specimen is a slotted plate 12×8 in. with a central groove confined to the mid-section of the length (Fig. 13). The degree of restraint is altered by changing the length of the slots and is expressed



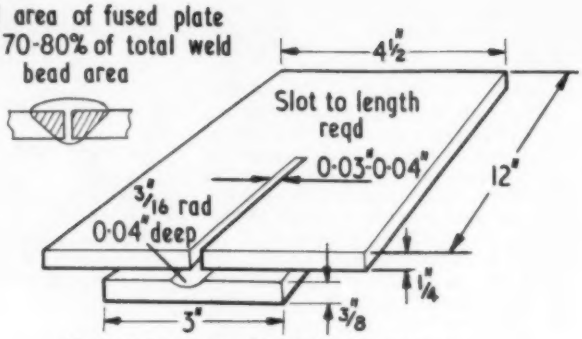
12—*Navy 'torture' test*



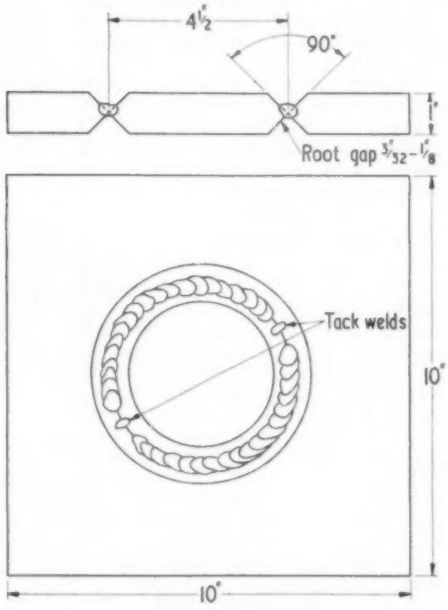
13—*Lehigh restraint specimen*



14—*Naval Research Laboratory restraint test specimen*



15—*B.W.R.A. butt weld slotted plate specimen*



16—*Circular patch test specimen*

numerically by the width of the specimen between the bottom of the slots. Different groove lengths are required for different thicknesses of material so as to provide sufficient restraint to cause cracking. Single or multiple deposits are made. Cracking is assessed by micro-examination. Several specimens are required to gain a positive result.

(18) Naval Research Laboratory Specimen

This type of specimen (Fig. 14) was developed to overcome the disadvantage of the Lehigh specimen for which several tests have to be made to determine the restraint necessary to cause cracking. The test consists of a plate 12×8 in. with a central groove along the length extending from the edge to a distance of 9 in., where a 1 in. dia. hole is drilled. This arrangement imposes along the weld length varying degrees of restraint which is at a minimum at the edge where welding is commenced and at a maximum at the hole where the welding is completed. Weld-metal cracking starts outwards from the hole, and the extent of cracking (crack length) is a measure of the crack susceptibility.

(19) B.W.R.A. Butt Weld Slotted Plate Test

Another test similar to the N.R.L. specimen is the test developed at B.W.R.A. for evaluating the cracking tendency of aluminium metal-arc electrodes (Fig. 15). Experiments indicate that the principle involved could also be applied to provide a cracking test for welds made by other processes, *e.g.*, argonarc or self-adjusting arc. In the original work on H.10 alloy the test weld was deposited along the open-enclosed slot in a rectangular plate ($12 \times 4\frac{1}{2} \times \frac{1}{4}$ in.) using a 6 s.w.g. electrode. The joint geometry of the slot can be varied to suit the particular operation in mind.

The welding conditions used should provide full plate penetration at a welding speed of about 15 in./min, and also 70–80% dilution of the filler additions by the plate.

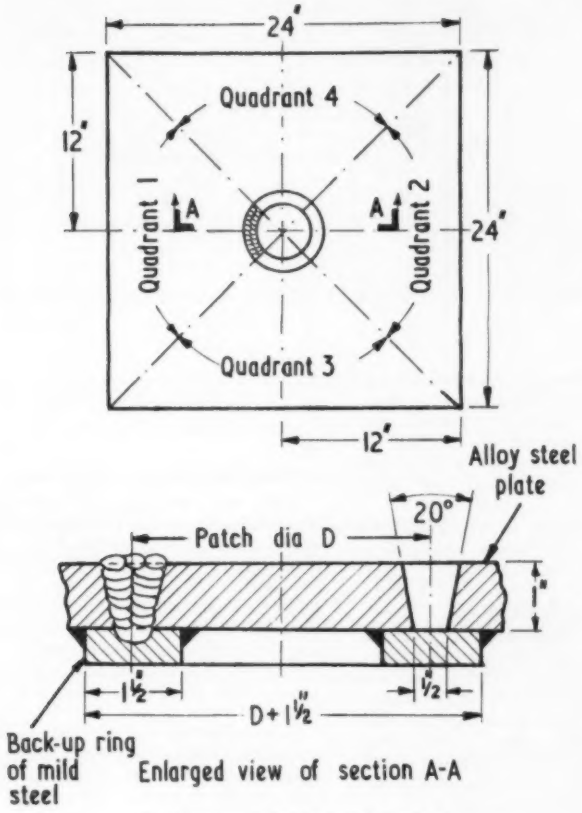
The minimum slot length at which crack-free welds are produced is termed the cracking index for the electrode, and is expressed as that length in inches.

(20) Circular Patch Test

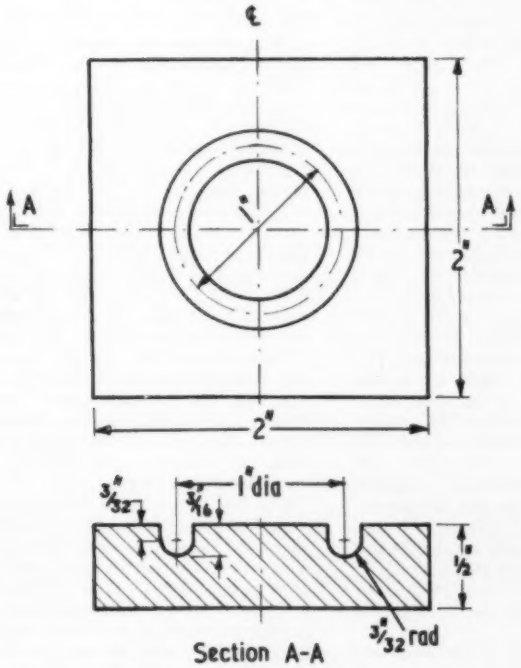
This test consists essentially of welding back a circular disc into a square plate from which it has been cut. It has been mainly used to investigate cracking in steels.

A typical design is shown in Fig. 16. The centre patch is tacked in two places and then one run is deposited in the groove. The weld is deposited slightly short of the tacks and the weld craters are left open.

The extent of cracking is measured and expressed as a percentage of the



17—*Navy-type circular patch specimen*



18—*Circular groove specimen*

total circumferential length of weld metal.

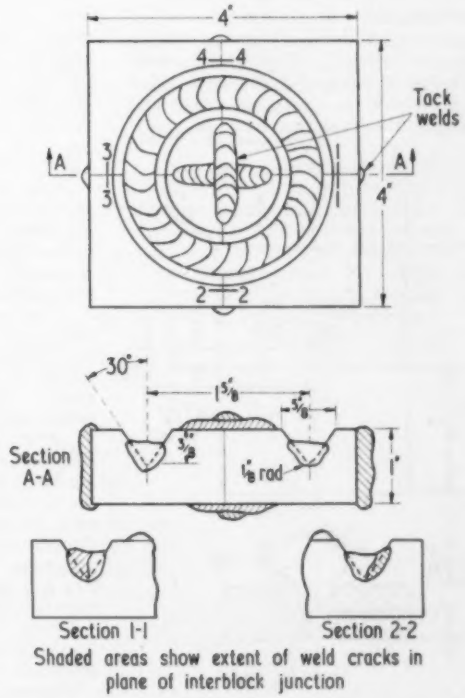
(21) Navy Type Circular Patch Specimen

Another type of patch test is that developed in the United States by the Navy Department, Bureau of Ships, for the qualification of low-hydrogen low-alloy electrodes (Military Specification MIL-E-986 (Ships)) (Fig. 17).

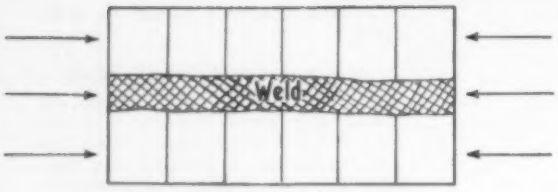
The weld is deposited using a block sequence in which one block is completely welded before starting the next. After welding the first block, the block diametrically opposite is welded. The third and fourth blocks are welded similarly. After completion of welding, the specimen is inspected visually for cracks. If apparently sound, weld-metal hardness and Charpy (keyhole) impact values are determined from sections cut from the joint.

(22) Circular Groove Test

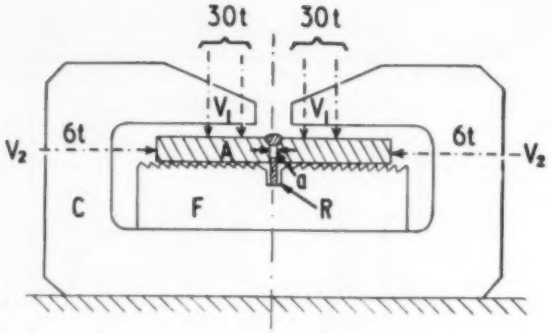
This test has been found suitable for evaluating the cracking tendency of many types of weld metal (Fig. 18). A circular groove $\frac{3}{16}$ in. deep is machined on a 2 in. square face of a block. Filler metal to be tested is then deposited in the groove under controlled conditions. When the test is used for assessing the low-temperature crack susceptibility of weld metal, the weld after completion is usually cooled rapidly by means of air jets placed at a specified distance above



19—*Segmented groove test specimen*



20—*Assembly of bars for finger test*



22—*FISCO test arrangement*

the block. The total crack length is measured and expressed as a percentage of the circular weld length.

(23) Segmented Circular Groove Test

This test is a modification of the circular groove test and is usually only used for assessing the hot-crack susceptibility of weld metal (Fig. 19). It was originally developed to evaluate the 'notch extension' cracking encountered when welding buckets to gas-turbine discs.

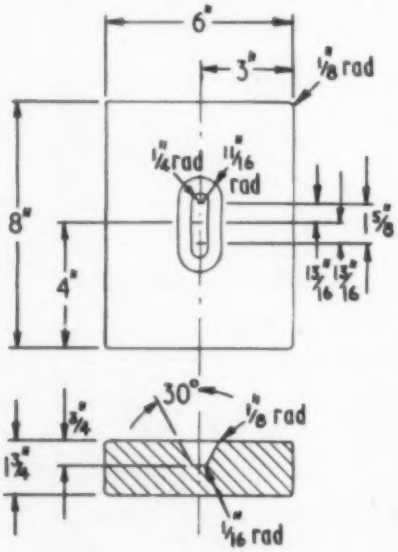
The four segments, of which the abutting edges are usually machine finished, are first tacked together, and then the test weld is made in one run.

The extent of cracking is determined by breaking apart the segments and noting the cracked (oxidized) area.

(24) Finger Test

This is another test used for 'notch extension' cracking. Figure 20 shows the essential feature of the test. Bars 2·5 in. × 0·650 in. × variable widths ($\frac{1}{4}$–1 in.) are fitted together in a clamping jig with a fixed pressure established by a torque wrench. A fusion weld or bead weld is then deposited across the assembly. The severity of the test is varied by altering the bar widths, the greater the bar width, the greater being the cracking.

The crack length is measured by breaking apart the fingers and noting the cracked area (see Test 23).



21—*Cast iron test block*

(25) Cast Iron Cracking Test

This test is essentially a grooved retraining block which has been cast (Fig. 21). The groove is cleaned with a small wheel or rotating burr before being welded. The test is used to discriminate between filler metals and welding processes for welding grey and nodular cast irons. The groove is filled with the filler metal under test.

The test block is examined visually during and after welding for the presence of weld- and base-metal cracks. If the weld is sound, a transverse 0·505 in. dia. tensile specimen can be machined from it for testing.

(26) FISCO Test

Basically the test consists of depositing one or more successive beads in a gap formed between two rigidly clamped metal plates. A specially designed jig is required (Fig. 22). This comprises a solid C-shaped high-tensile steel casing *C*, which is nearly closed-in on top, a solid slab *F*, which is serrated to prevent the plates moving, and a hard steel spacer *R*, which is placed between the plates to maintain a constant gap. The plates are clamped by means of vertical V_1 and horizontal V_2 screws. Plate thicknesses of 1–40 mm can be accommodated, with gap widths, which alter the severity of the test, of 0–6 mm. The maximum and minimum widths of plates that can be used are 120 and 70 mm respectively. The plate length is 200 mm. The gap width used must not be greater than the diameter of the electrode.

Crack lengths are measured after breaking the specimen to expose the fractured surface.

The crack sensitivity of the electrode is expressed by the ratio:

$$Fa = \frac{\text{Total length of crack}}{\text{Average length of four beads}} \times 100\%$$

where a is the gap width.

(27) Boudreau Sheet Cracking Test

This test consists of applying a definite steady tensile load in a sample of sheet while an inert-arc weld is made normal to the axis of loading. No filler is added.

The stress level at which cracking is initiated is the index of the weld cracking susceptibility of the material.

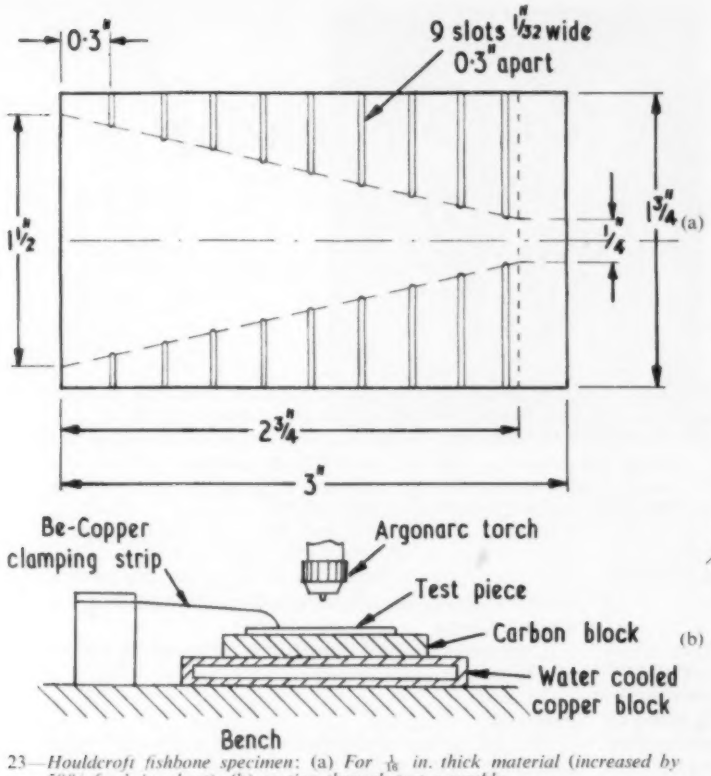
The size of specimen normally used is $1\frac{7}{8}$ in. wide by $5\frac{7}{8}$ in. long, but other sizes can be used.

In conducting the test the weld is commenced and completed away from the edge of the sheet, otherwise cracks can initiate from the sheet edges and give false results.

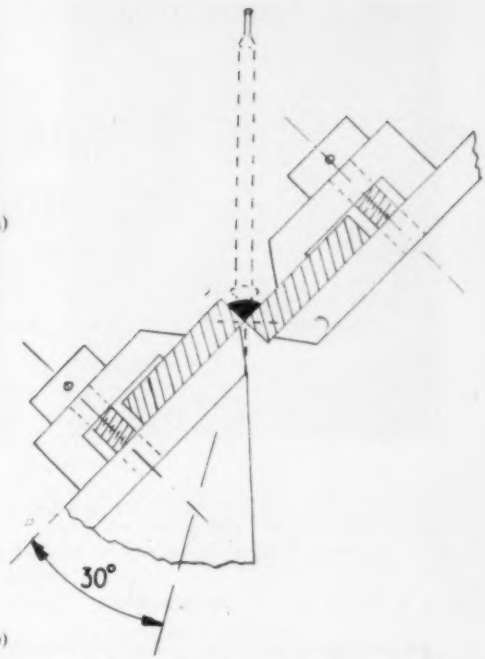
(28) Houldcroft Fishbone Type Test

This test was developed for assessing the cracking tendency of welds in sheet material welded by the argonarc process, with or without filler metal. It is based on the simple concept that if a weld run is started on the edge of a sheet, a crack can easily initiate and then propagate unless the restraint is in some way reduced. The present form of the test for $\frac{1}{16}$ in. thick aluminium alloys is shown in Fig. 23*a*. The restraint is gradually reduced by a series of slots of various depths cut into the sides of the test piece. The distance the crack progresses along the run, before the stress is relieved sufficiently to stop it, is the measure of the crack sensitivity of the alloy. Edge cracking in the parent material, parallel to the fusion line, is also observed in some cases and can be measured. Six tests are usually made and the mean crack length computed.

The test run is made down the centre line of the specimen (which is marked to assist the welder) starting from the edge where the slots are widest apart. Complete penetration must be obtained and a constant weld width maintained. Best results are obtained if manual welding is employed, for then the welder can vary his welding speed at the start and end of



23—*Houldcroft fishbone specimen*: (a) *For* $\frac{1}{16}$ *in. thick material (increased by* 50% *for* $\frac{1}{8}$ *in. sheet)*; (b) *section through test assembly*



24—*Principle of Murex hot crack machine*

welding and thus maintain a constant bead width. Mechanical welding is particularly troublesome when a range of materials is being investigated owing to the change in thermal properties.

The welding jig used need be very simple (Fig. 23*b*). A carbon block is an essential feature of the test; it conducts heat poorly compared with the metal but conducts the welding current efficiently and also provides a convenient starting-point for the arc. Fresh carbon blocks are used for each single test, thus ensuring that at the beginning of the test the carbon block is at room temperature.

(29) Murex Hot Crack Testing Machine

The operating principle of the machine is as follows: A fillet weld is deposited in a V formed between two small $\frac{1}{2}$ in. thick plates, one of which is rotated about the point of the V by a known amount, independently of the test weld contraction (Fig. 24). By varying the speed of rotation, the amount of strain imposed can be altered; the fixed length of the deposit sets a definite time of testing. In operating the machine a delay of 5 sec after the welder starts to deposit the test weld is allowed before rotation of the test plate is started.

Various speeds of rotation can be obtained; the strain developed is made proportional to the speed of rotation and is a function of the V angle, which is always initially 90°. The maximum angle that can be obtained is 120°. Crack length is a measure of the crack susceptibility.

(30) Prokhorov Machine

This test is essentially a Russian development of the Murex Hot Crack Machine. Here, however, the test plate consists of a number of fingers which are rotated (by a series of cams) in turn at different rates as the weld is deposited.

The strain to cause cracking is a measure of the crack sensitivity.

Cover illustration: A view of the Bristol Siddeley 'Stentor' rocket engine which is used to power the British 'Blue Steel' missile.

The Stentor burns kerosene with hydrogen peroxide in high-pressure combustion chambers. Welding is used extensively in the fabrication of the heat-resisting materials used in the construction of the rocket engine, and contributes greatly to its high performance.

AUTUMN MEETING 1960

High-Frequency Induction Brazing of Small Components

IN ARGON STREAMS

By P. M. Bartle, L.I.M., *and J. G. Young*, B.SC.

Some experiments on the use of high-frequency induction brazing in argon streams for joining small components in similar and dissimilar metals are outlined. It is shown that filler metals are available for the successful joining of a range of material combinations. The technique is particularly valuable for joining parts made from non-film forming materials, although the latter may be successfully brazed if pre-plating is employed.

Introduction

IT IS suggested that h.f. induction brazing in argon streams is a valuable technique for joining small components, in both similar and dissimilar metals. It requires the minimum of operational skill, and with a little experience can be as easily employed for one-off jobs as for production runs. No flux is employed and since protection is by external streams of argon the time spent in setting up, purging, and dismantlings such as would be involved if a chamber were used, is reduced to a minimum.

In the course of a recently completed contract, B.W.R.A. successfully applied this technique to a batch of components requiring a very high standard of joint leak-tightness. It was considered that the experience gained on a particular combination of metals could be readily extended to a range of materials, and this paper reports the results of a preliminary study of the use of the technique for joining certain similar and dissimilar metals.

The basic type of joint chosen (Fig. 1*a*) was the tube-to-plate assembly, since it is of frequent occurrence and lends itself to h.f. induction heating methods. Titanium was chosen as the plate material for a large proportion of the experiments reported, for two reasons:

(i) Some experience had already been gained with the material
(ii) Titanium was known to be a difficult material to braze owing to its propensity for alloying with many commonly used filler alloys to produce brittle intermetallic compounds.

Materials

The sheet materials used were commercial purity titanium (I.C.I. 130) $\frac{1}{16}$ in. and $\frac{1}{8}$ in. thick, and 14 s.w.g. 18/8 titanium stabilized stainless steel. For joints involving studs commercial purity titanium bar was employed.

Tube materials and dimensions are listed in Table I and filler wires in Table II.

Apparatus

The h.f. power was supplied by a 350 kc/sec valve generator, with a maximum output of 6 kW (BS.

Table I

Dimensions of tube materials

Material	*External Dia., in.*	*Wall Thickness, in.*
Copper	0·125	0·032
Mild Steel	0·124	0·020
Stainless steel (unstabilized)	0·124	0·032
Stainless steel (stabilized)	0·102	0·019

Table II

Filler materials used

Reference	*Nominal Composition, %*	*Dia. Used, s.w.g.*	*Temperature, °C., of Solidus*	*Liquidus*
A	Ag 72 Cu 28	22	779	
B1	Ag 68·4 Cu 26·6 Pd 5	24	807	810
B2	Ag 58·5 Cu 31·5 Pd 10	24	824	852
B3	Ag 65 Cu 20 Pd 15	24	850	900
B4	Ag 52 Cu 28 Pd 20	24	879	898
B5	Ag 54 Cu 21 Pd 25	24	901	950
C	Au 85 Ni 15	24	950	
D	Ag100	16	960·8	
E	Ag 85 Mn 15	22	960·8	976
B6	Ag 95 Pd 5	24	970	1010
B7	Ag 75 Pd 20 Mn 5	24	1000	1120
F	Au100	22	1063	
G	Cu 82 Pd 18	24	1080	1090
H	Cu100	28	1083	
B8	Ag 64 Pd 33 Mn 3	24	1180	1200
I	Pd 60 Ni 40	28	1237	

Manuscript received 3rd August 1960.
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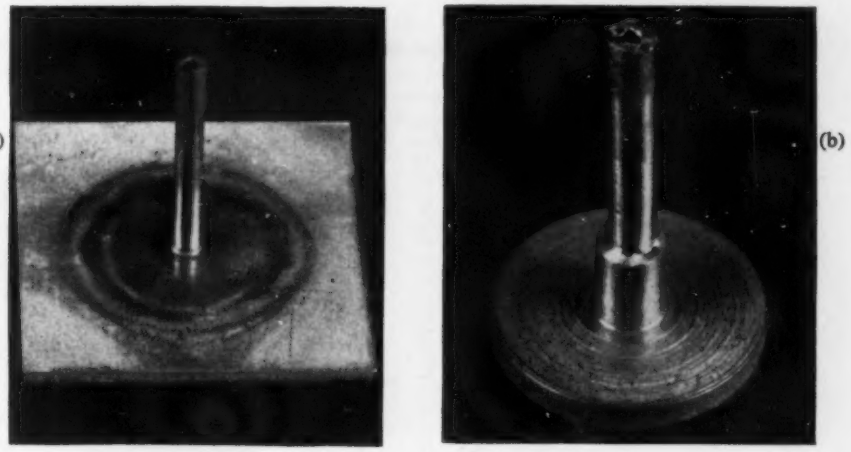
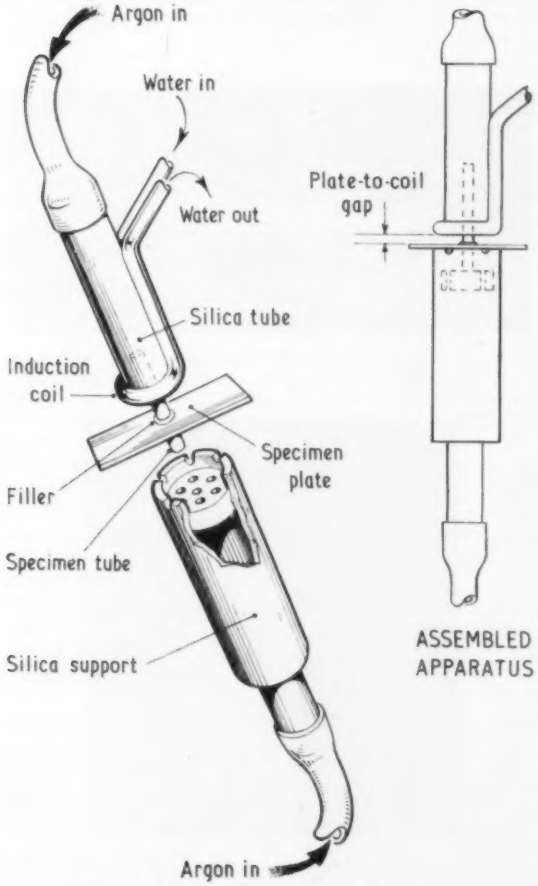


1—*Brazed joints:* (a) *Tube/plate;* (b) *tube/stud*

1799:1952), to which was connected a single-turn coil of copper tube *via* a step-down transformer. The lead-in pipes rose vertically from the plane of the $\frac{7}{16}$ in. internal diameter coil, as indicated in Fig. 2.

Shielding argon was separately supplied to both the top and underside of the specimen through silica tubes. The upper tube was bonded to the coil, whilst the lower formed a specimen support stand as also indicated in Fig. 2.



2—*Arrangement of apparatus for brazing*

Experimental Technique

Preparation of components

All components were abraded with fine emery paper to give a bright finish and were finally degreased before assembly. Filler wires were formed into rings, and were degreased and preplaced before brazing. In one series of tests the stainless steel tube was lightly nickel plated.

Brazing sequence

The prepared components were placed on the support stand and positioned axially within the coil, the exact position of the sheet relative to the bottom of the coil being determined by the thickness and nature of the materials being joined, as indicated in Table III.

Argon purging was carried out for 30 sec, using flow rates of 25 cu.ft/hr for each supply, before the h.f. power was switched on. A constant output setting was employed. The end point of brazing was determined by visual observation of the joint in most instances, although with tube/stud joints, automatic time control was employed. Argon flow was continued until the specimens were cold.

Examination and testing

Examination techniques included visual inspection, microscopic examination, and mechanical testing. The test which involved direct tension on the tube was

Table III
Plate-to-coil gaps used

Plate Material	*Thickness, in.*	*Plate-to-Coil Gap, in.*
Titanium	$\frac{1}{16}$	0·0625
Titanium	$\frac{1}{8}$	0·050
Stainless Steel	14 s.w.g.	0·030

Table IV

Wetting characteristics of different filler and base metal combinations

Filler Alloy	*Joint Composition and Metal Wet*							
	Plate Ti	*Tube Cu*	*Plate Ti*	*Tube MS*	*Plate Ti*	*Tube SS*	*Plate SS*	*Tube SS*
A	G	G	G	G	G	G	S	S
B1	G	G	G	G	G	G	S	S
B2	G	G	G	G	G	G	P	P
B3	G	G	G	G	G	G	S	S
B4	G	G	G	G	G	G	S	S
B5	G	G	G	G	G	G	P	P
C	—	—	P	P	P	P	G	G
D	—	—	G	P	G	P	P	P
E	G	G	G	G	G	G	G	G
B6	—	—	G	P	G	P	P	P
B7	—	—	G	G	G	G	P	P
F	—	—	G	G	*	*	G	G
G	—	—	G	G	G	G	—	—
H	—	—	G	G	G	G	G	G
B8	—	—	G	G	G	G	P	P
I	—	—	—	—	G	G	P	P

* With Ti and SS joined with Alloy F poor results very similar to Ti wet with Alloy C are obtained.
G = Good P = Poor S = wetting with considerable superheat.

employed to assess joint consistency and was used for a limited number of systems only. The actual load values obtained for different series of specimens are not comparable owing to the variations in specimen dimensions noted in Tables I and V.

Results

Wetting behaviour

Wetting behaviour as assessed by visual and micrographic examination is summarized in Table IV. Wetting of titanium was easy with all fillers except Alloy C, and, as expected, with many alloys there was a strong tendency to erosion and excessive alloying. With silver (D), and gold (F), good wetting was obtained without alloying. Alloy B6 also gave good wetting without excessive alloying.

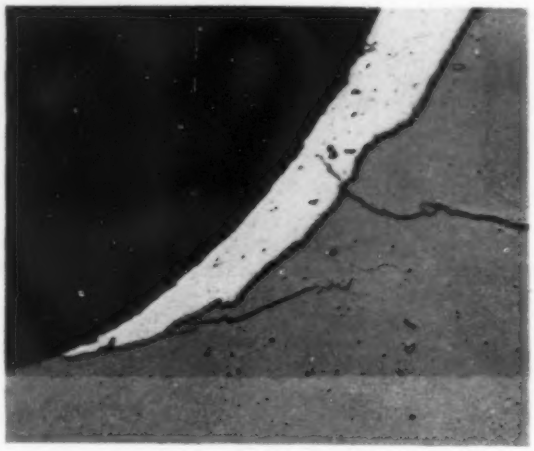
The wetting of copper presented no problems with the limited range of fillers of suitable melting point. The wetting of mild steel in combination with titanium proved difficult only with Alloys D, B6 and C.

Stainless steel (both Ti stabilized and unstabilized) in combination with titanium was easily wetted by all fillers except those which did not alloy excessively with titanium *i.e.*, Alloys F, D, B6, and C. Metallographic examination showed a phase rich in Ti adjacent to the stainless steel tube, as shown in Fig. 3.

In the case of stainless-steel/stainless-steel joints, experiments on which were prompted by the results obtained on the stainless-steel/titanium combination, wetting was generally much less satisfactory, as will be observed from Table IV. Some alloys behaved better with a high degree of superheat, and this has been noted in the table. One specimen was prepared with a composite filler consisting of a ring of copper-silver eutectic and a ring of titanium wire, and this filler wet the stainless very well. However, it contained rather too much titanium and consequently its joint filling properties were poor. A further specimen was brazed with silver-copper eutectic using nickel plating as a pre-treatment procedure and this eliminated the need for superheat (Figs. 4 and 5).

Joint filling

Brazing clearance was not systematically investigated but gaps of from nothing to 0·002 in. were



3—*Stainless steel/titanium brazed with Alloy B2, showing Ti-rich phase adjacent to the stainless steel and the cracking in this phase* ×150

4—*Nickel plated stainless steel/stainless steel brazed with Alloy A, showing good wetting of the nickel plated stainless steel* ×200

5—*Stainless steel/stainless steel brazed with Alloy A under similar conditions to the specimen of Fig. 4 showing poor wetting of unplated stainless steel* ×100

Table V

Strength tests on brazed joints (room temperature)

Plate	*Materials Tube*	*Filler*	*Range of Breaking Loads, tons*	*Position of Fracture*	*Number of Joints with Max. Properties*
$\frac{1}{8}$ in. CP Ti	Mild Steel	A	0·180–0·190	Tube	3 out of 3
		B2	0·185–0·190	Tube	3 out of 3
		B5	0·190–0·195	Tube	3 out of 3
		B7	0·165–0·190	Joint or tube	2 out of 3
		F	0·115–0·170	Joint or tube	0 out of 3
		H	0·180	Tube	2 out of 2
	18/8 SS unstabilized	A	0·225–0·235	Joint	0 out of 3
		B2	0·125–0·360	Joint	1 out of 3
		B4	0·105–0·220	Joint	0 out of 3
		G	0·125–0·265	Joint	0 out of 3
	18/8 SS stabilized	A	0·105–0·170	Joint	0 out of 3
		B1	0·040–0·180	Joint	0 out of 3
		B4	0·125–0·190	Joint	0 out of 3
		B5	0·160–0·220	Joint	2 out of 3
$\frac{1}{16}$ in. CP Ti	Copper	A	0·105–0·130	Joint or tube	2 out of 3
		B1	0·130	Tube	3 out of 3
		E	0·100–0·125	Tube	0 out of 3
	Mild Steel	A	0·195	Tube	3 out of 3
		B1	0·185–0·195	Joint or tube	3 out of 3
		G	0·195	Joint or tube	3 out of 3
CP Ti Stud	18/8 SS unstabilized	A	0·220–0·345	Joint	0 out of 6
		B4	0·300–0·360	Joint	1 out of 3
	18/8 SS stabilized	A	0·160–0·215	Joint	2 out of 3
		B1	0·190–0·205	Joint	0 out of 3
		B2	0·215–0·220	Joint	2 out of 2
		B4	0·130–0·180	Joint	0 out of 3
		E	0·105–0·210	Joint	0 out of 3
14 s.w.g. SS	18/8 SS unstabilized	C	0·315–0·380	Joint or tube	2 out of 3
		H	0·275–0·305	Joint	0 out of 3
		E	0·125–0·165	Joint	0 out of 3
	18/8 SS stabilized	F	0·210–0·215	Tube	3 out of 3

employed. Generally speaking, the minimum clearance was required for joints that included titanium, and the larger clearances were needed for the stainless/stainless combination. Where wetting of both components was satisfactory, joint filling was also normally good, but the particular type of specimen used in the investigation does not represent a very severe test of joint filling ability.

Cracking

Cracking was a problem in some instances, particularly where the freezing range of the filler was large or extensive alloying with titanium occurred. Differential expansion effects were a contributory cause of cracking, particularly when stainless steel formed part of the combination. The latter problem was alleviated to some extent by the use of a stud type of joint (see Fig. 1*b*). An example of cracking in the titanium-rich phase is shown in Fig. 3.

Details of cracked specimens have not been tabulated, but cracking susceptibility has been taken into consideration in preparing the general summary of suitability of fillers presented in Table VI.

Strength tests

Detailed room-temperature strength test results are given in Table V. The range of loads over which specimens fractured is given, and an indication of consistency of joint quality may be obtained from the proportion of joints giving the maximum strength with each tube material. Good quality joints were at least as strong as the tube material in the case of mild-steel/titanium and copper/titanium but high strength was more difficult to attain with stainless-steel/titanium, and failure always occurred in the joint, albeit sometimes at stress levels very near to the strength of the tube material.

No strength tests were carried out with nickel plated tubes nor with filler materials containing titanium.

Discussion

There is no apparent difficulty in finding suitable filler materials for induction brazing in argon streams provided that the parent materials are non film-forming. (Titanium dissolves its own oxide film.) Although there was titanium in all the materials under review it may be reasonably inferred that its presence is not essential, and in fact small components of dissimilar non film-forming alloys have been satisfactorily brazed in the laboratory using this technique.

For the copper/titanium joint combination, the choice of filler materials is limited by melting point considerations, and the most satisfactory fillers are the silver-copper-palladium and silver-copper eutectics. It was not found possible to produce a joint without extensive alloying with the titanium but nevertheless sound and strong joints were obtained.

With titanium/mild-steel joints, the choice of satisfactory fillers is wider, the best results having been obtained with copper, silver-copper, copper-palladium, and silver-copper-palladium alloys. Copper would, in fact seem to be an essential ingredient for good wetting and joint filling in this combination.

Table VI

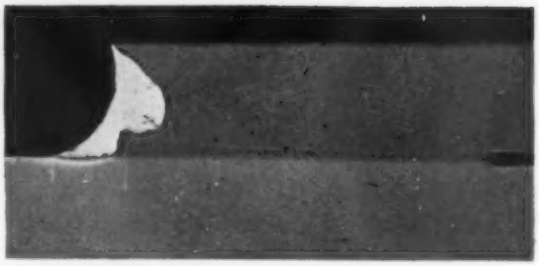
Summary of suitability of fillers for various joint combinations without plating

Filler Alloy	*Joint* Ti/Cu	Ti/MS	Ti/SS	SS/SS
A	S	S	S	U
B1	S	S	S	U
B2	S	S	S	U
B3	S	S	S	U
B4	S	S	S	U
B5	S	S	S	U
C	MP	U	U	S
D	MP	U	U	U
E	MP	S	S	S
B6	MP	U	U	U
B7	MP	U	U	U
F	MP	*	U	S
G	MP	S	S	—
H	MP	S	S	S
B8	MP	U	U	U
I	MP	—	U	U

* Alloy F is suitable for joining mild steel and Ti at slow to moderate heating rates but will not produce a good joint with superheating.
S = Suitable U = Unsuitable MP = melting point too high.

Satisfactory joints, though possible, are less easy to make when stainless steel is included in the combination. Two types of 18/8 stainless steel tube were experimented with, an unstabilized variety and one stabilized with a nominal 1% Ti. Contrary to popular belief, the Ti-stabilized variety did not give increased wetting problems, and indeed the strength tests indicate that good joint production was perhaps slightly easier than with the unstabilized steel.

A significant feature of the wetting test results, reported in Table IV, is the difference in the behaviour of various fillers on stainless steel tubes with the two different plate materials, namely titanium and stainless steel. The improvement in wetting of the stainless tube resulting from the solution of titanium in the filler alloy is noticeable and has been confirmed by brazing a stainless/stainless combination with a filler containing a large proportion of titanium, when wetting behaviour was extremely satisfactory. In practice a smaller proportion of titanium in the filler would probably improve joint filling characteristics. The use of direct nickel plating on stainless steel has a beneficial effect and allows the use of fillers that would otherwise not wet the stainless steel or would require considerable superheat.



6—*Stainless steel/titanium stud brazed with Alloy B4* ×23

The problem of cracking, which was thought to occur because of differential expansion effects between stainless steel and titanium, was significantly reduced by the use of the stud type of joint rather than the tube-to-plate joint. Strength was not improved, however, owing to unsatisfactory joint filling. It is thought that a different joint design would give improved results. The filling characteristics of the stud joint used are illustrated in Fig. 6.

The summary in Table VI indicates the suitability of various fillers for each combination of parent materials. In compiling this table, the authors have taken into account visual appearance, metallographic evidence and, where applicable, consistency of joint production as indicated by mechanical tests.

Conclusions

High-frequency induction brazing in argon streams is a technique worthy of consideration when circumstances do not justify the provision of a hydrogen, vacuum, or inert-gas chamber. A suitable filler may be found for most combinations of materials, although in some instances pre-plating of one or both of the components may be necessary.

AUTUMN MEETING, 1960

Use of Welding in Chemical Plants in the U.K.A.E.A.

By F. S. Dickinson, A.M.I.MECH.E., A.M.INST.W., *and B. Watkins*, M.SC., A.I.M.

General features of 18% Cr–13% Ni–Nb fully austenitic stainless steel, as widely used for chemical plants handling radioactive processing liquors, are discussed. Indications are given of the controls applied to ensure freedom from cracking, and methods of pipe branch connections are presented.

A unique problem facing the designers of such chemical plant is that of 'criticality'. This entails careful design to avoid chain reactions when highly enriched materials are involved, and the systems to safeguard against this hazard are treated in some detail.

The difficulties encountered during the fabrication of components in Monel and Inconel are described; it appears that consistency of quality cannot be assured with the same certainty as with the stainless steels. For most of the vessels manual metal-arc methods were used, but for pipework and where access for welding from one side only prevailed argonarc techniques with appropriate filler wires were essential.

Metallurgical studies of some corrosion failures during the initial operation of plant manufactured from nickel-bearing materials indicated that better corrosion resistance, for the particular service conditions, could be obtained when niobium was excluded from the weld metal.

THE STANDARD of weld quality demanded in chemical plants associated with the U.K. Atomic Energy Programme is extremely high, even when the materials contained have not been radioactive. Certain vessels are peculiar to the nuclear field in that they contain highly radioactive materials such that their repair is impossible, or are of unusual shape (for criticality reasons), or handle highly enriched materials of considerable financial value.

The Chemical Separation Plant for the extraction of plutonium from irradiated fuel elements at Windscale has now completed about 10 years' service without leakage. This is particularly noteworthy since some 5000 tons of welded plate ranging from ¼ in. to 1¼ in. thick, together with approximately 50,000 pipe butt welds, were used in its construction.

The increased volume of irradiated fuel to be processed from nuclear reactors operated by the U.K.A.E.A., and from the gas cooled reactors now being constructed for the C.E.G.B. nuclear power programme, has made necessary a considerable extension to chemical processing facilities, and the fabrication of vessels in 18% Cr–13% Ni–Nb stainless steel is still continuing on a large scale.

This paper presents some of the problems encountered in the construction of these vessels, and in particular indicates the welding techniques developed, with the co-operation of British Industry, in the manufacture of high-quality products.

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The authors are with the D. and E. Group, R. and D. Branch of the U.K.A.E.A., Culcheth. 591

Welding Fully-Austenitic Stainless Steels

It is now well known that fully-austenitic stainless steel of 18% Cr–13% Ni–Nb composition has been extensively used in the construction of chemical plant handling highly radioactive process liquors. The techniques adopted for the welding of this material to a virtually defect-free standard have been adequately described previously.[1]

This material was selected on the grounds of improved corrosion resistance over that obtainable with 18% Cr–8% Ni steel for varying concentrations and temperatures of nitric acid solutions. Table I indicates the relative corrosion rates of these materials and the rate of attack to be expected when metal-arc welding is used.

The susceptibility to cracking of a fully-austenitic steel makes successful welding with a deposit of matching composition largely dependent on the degree of restraint imposed and the cooling rate of the weld. Since joint geometries differ so widely, the general application of a reliable method must cater for the worst conditions, and so electrodes have been used to give a duplex deposit of austenite and ferrite. Applying the limits of composition given in Table II for manual metal-arc electrodes, it is impossible to obtain a fully-austenitic undiluted deposit. It will be noted that the

Table I

Relative corrosion rates of 18/13 and 18/8 parent plate and welds made with 18/9 metal-arc electrodes

Material	*HNO_3 Concentration* 3 *N*	6 *N*	12 *N*	*Duration of Test, hr*
	Mean Penetration Rate, mm/yr			
18/8/Ti plate	0·04	0·18	1·5	1000
18/9/Nb weld on 18/8Ti	0·02	0·18	1·0	2500
18/13/Nb plate	0·01	0·04	0·24	1000
18/9/Nb weld on 18/13/Nb	0·01	0·04	0·38	2500

All solutions boiling under reflux condensers.

Table II

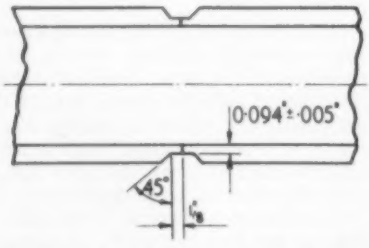
Composition limits for 18% Cr–9% Ni electrodes

	Minimum, %	*Maximum, %*	
C	—	0·1	
Si	—	0·8	
Mn	0·75	1·5	
Cr	18	20	Cr/Ni ratio shall be between 2·0 and 2·4
Ni	8	—	
Nb	10 × Carbon		

percentages of Cr and Ni are inter-related, and it can be shown, by using the well-known Schaeffler diagram, that electrodes can contain between 2 and 16% ferrite, depending on the Cr and Ni equivalents. These extremes have never yet occurred, and experience over a number of years has shown a range of 6–9% to be possible.

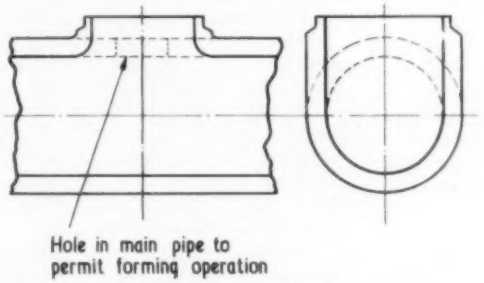
Welding with manual electrodes, to give a weld metal of controlled ferrite content, is a well proven practice. The increased dilution obtained in automatic welding would require a revision of the specification indicated in Table II, possibly varying according to the particular automatic method envisaged. The majority of welding is thus still being done by manual metal-arc methods, tungsten argonarc being applied on pipe welds or joints where access is only possible from one side.

Whilst metal-arc welding is invariably done in the downhand position, pipe welding techniques are applied in all positions and bring particular problems. For simple butt welds it has been found possible to control initial root bead penetration by using argon-arc welding alone, if the edges are prepared as shown in Fig. 1. A perfect abutment of root faces is necessary and careful control of dimensions is important for several reasons. The root face must be of sufficient depth to ensure consistency of penetration without being so thin as to allow burn-through when the joint is subsequently metal-arc welded. Flexibility is also useful and for this the somewhat generous 'land' of $\frac{1}{8}$ in. on each side of the joint line is adopted. Using this technique, inter-connecting pipework (generally the thinnest section of containment) is of uniform composition against the corrosive liquors being processed, and the welds have a somewhat improved corrosion resistance over those made in the main vessels by metal-arc methods and duplex electrodes.



1—*Weld preparation for 18% Cr–13% Ni–Nb pipe butt weld*

Difficulties in pipe welding, irrespective of material, reach a peak on branch connections. For 18% Cr–13% Ni–Nb pipe, in which the first run is argonarc welded, it becomes even more important to have accurate fit between the two members to be joined.



2—*'Pulled tee' branch weld preparation*

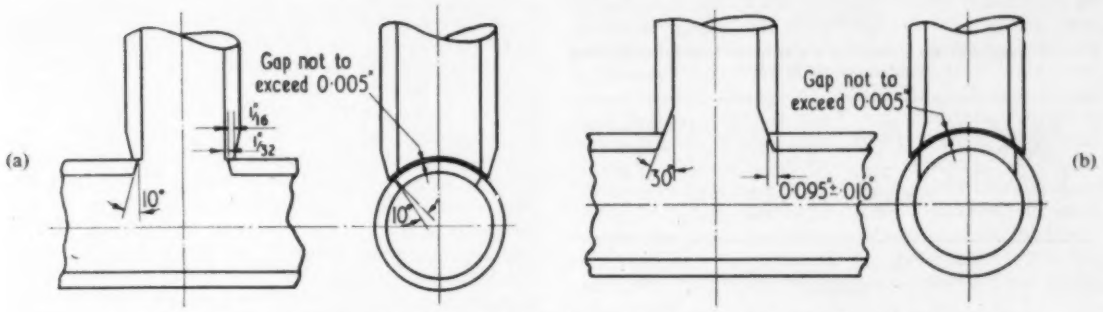
The ideal form for a branch connection would be a stub or tee joint (Fig. 2), but the heavy gauge wall used (Table III) makes the forming operation difficult. A number of preparations are in use which permit root fusion techniques to be applied (Figs. 3*a* and *b*) but careful hand fitting is necessary.

Backing sleeves or backing bars, whether of the same stainless steel, removable later by machining, or of copper, have been essential for making certain joints. Although these are accessible for welding from one side only, they are so rigid that root fusion methods (or indeed the use of ferrite-controlled filler wire and argonarc methods) result in major weld cracking. The increased volume of weld metal from metal-arc methods, coupled with faster welding speed, gives a more substantial first run with relatively rapid weld cooling. This, in conjunction with the duplex nature of the deposit after dilution, enables crack-free welds to be made. Removable copper backing bars are useful in providing a smooth penetration bead that requires no

Table III

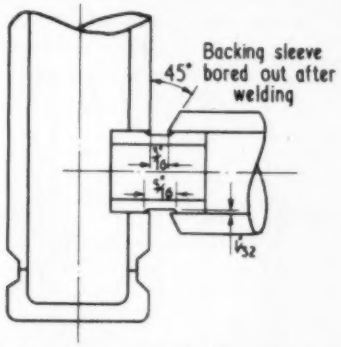
Pipe sizes in 18% Cr–13% Ni stainless steel

Nominal Bore in.	*Outside Dia., in.*	*Wall Thickness in.*
1	1 $\frac{11}{32}$	0·144
1$\frac{1}{2}$	1 $\frac{23}{32}$	0·160
2	2$\frac{3}{8}$	0·176
3	3$\frac{1}{2}$	0·192
4	4$\frac{1}{2}$	0·212
6	6$\frac{1}{2}$	0·232



3—*Branch pipe weld preparations for 18% Cr–13% Ni pipe:* (a) *Original form;* (b) *modified form*

subsequent machining and still permitting the direct use of metal-arc welding. Care, however, is necessary in making join-ups, and craters must be meticulously cleaned to prevent crater cracks being left unfused on continuing the weld run. Metallographic examination has shown that no copper contamination occurs.



4—*Backing sleeve preparation for metal-arc welding*

The method of fitting a backing sleeve inside the branch pipe (Fig. 4) avoids the need for precise fitting. It is of course necessary to be able to bore out the backing sleeve after welding is complete so that a crevice-free surface is presented to the corrosive medium. Although it must be admitted that the weld metal in contact with the corrosive medium is no longer the same as the base material the rate of attack will be no greater than that experienced on the metal-arc welds in the vessel seams; the technique has further merit because of reduced distortion. When closure near to the branch is demanded distortion is important, and circularity of the main pipe is essential to permit root fusion methods to be used on this closing weld.

Some chemical plant made in 18% Cr–13% Ni–Nb stainless steel does not operate in a highly active environment and thus can be inspected or repaired if necessary. One such plant for dissolving plutonium slags suffered severe weld corrosion in a relatively short time when metal-arc welding with ferrite-controlled electrodes was used. This preferential weld attack, arising from an appreciable fluoride content in conjunction with nitric acid, was considerably reduced by using a 25% Cr–20% Ni–Nb deposit. The use of such deposits is dependent on the geometry of construction and cannot be recommended for general application. The degree of restraint in this case was such that cracking did not take place. Moreover, as the weld metal was more noble than, and thus cathodic to, the 18% Cr–13% Ni–Nb parent plate, selective weld metal attack was avoided. The relative corrosion resistance of a number of different weld metal compositions in nitric–hydrofluoric acid mixtures has been tested; although the nature of the attack makes quantitative comparison difficult, it is apparent that a 65% Ni–35% Cr alloy has useful possibilities. At present, however, such welds can be made only by inert-gas welding techniques. Furthermore, care has to be observed in welding since random orientation cracking can result if restraint is high. The somewhat improved resistance of a 28% Cr–20% Ni deposit over that of 25% Cr–20% Ni–Nb is noteworthy since more freedom of application is theoretically possible; but such deposits have not yet undergone service operation.

Criticality Considerations

A unique problem facing designers of chemical plant for the processing of spontaneously radioactive materials is that of avoiding a 'critical mass'. If either Pu 239, U 235, or U 233 is allowed to accumulate under certain conditions, a chain reaction can start which results in a large and rapid build up of heat, with serious radiation hazards. In view of this criticality hazard these vessels are designed in such a way that the mass of fissile material present cannot assume critical proportions.

It is important to realise that vessels designed to conform to criticality requirements can still be classed as either "active" or "inactive" although both are handling potentially radioactive materials. "Active" vessels are those in which the fission products, arising from fuel irradiation in the nuclear reactor, are still present in the material being processed, as well as the Pu 239 and the residue of U 238 and U 235. These fission products radiate high levels of beta and gamma activity and therefore demand appropriate shielding. For these vessels 18% Cr–13% Ni–Nb stainless steel is used with full weld radiography since repair is not possible after installation. "Inactive" vessels are hence handling Pu 239 and the remaining U 238 and U 235 after the extraction of the gamma radiating fission products, and thus can be inspected and repaired

Table IV

Critical conditions for sustaining a chain reaction in a spherical vessel immersed in water

Fissionable Material	*Mass, g*	*Volume, litres*	*Concentration, g/litre*
U 235 (93·5%)	790	5·2	11·6
U 233	588	3·5	10·9
Pu 239	509	5·0	7·3

Table V

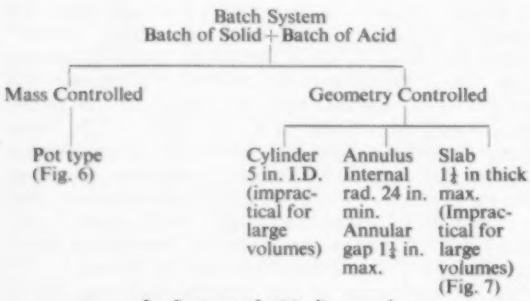
Critical dimensions for water-reflected vessel types

Fissionable Material	*Sphere dia., in.*	*Cylinder dia., in.*	*Slab Thickness, in.*
U 235 (93·5%)	8·5	5·3	1·3
U 233	7·4	4·5	0·5
Pu 239	8·3	5·0	1·7

should this ever be necessary. Such vessels are made from 18% Cr–8% Ni–Nb (or Ti) stainless steel and allow the designer more freedom, since the requirement of full weld radiography is not so essential.

Factors to be considered in design include the mass and volume of the material to be processed together with its concentration, the amount of neutron escape through the walls of the vessels, the possible reflection back of neutrons into the system from the surroundings, the use of absorbing materials such as cadmium or boron in the processed materials, and the likelihood of inter-action between neighbouring vessels handling these materials.

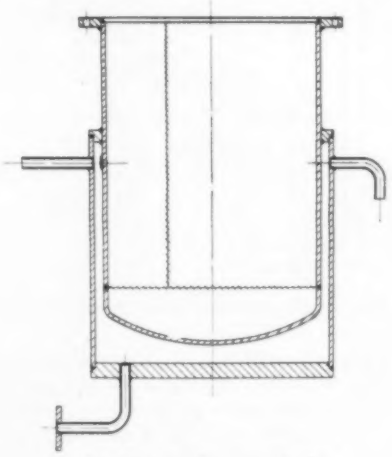
For any particular set of plant conditions, there is a certain critical mass, volume, and concentration of fissionable material below which a chain reaction cannot be sustained. Since a spherical container has a minimum surface-area/volume ratio, the neutrons escaping during reaction will be a minimum. If it is now assumed that such a container is completely immersed in water of infinite volume, the majority of escaping neutrons will be reflected back into the system. Table IV lists the limits below which reaction will not be sustained under the worst conditions as above, from which it will be appreciated that only a small quantity of material could be processed in any one container. Fortunately, by increasing the surface-area/volume ratio, even with maximum reflection back


Batch System
Batch of Solid + Batch of Acid
Mass Controlled
Geometry Controlled
Pot type (Fig. 6)
Cylinder 5 in. I.D. (impractical for large volumes)
Annulus Internal rad. 24 in. min. Annular gap 1½ in. max.
Slab 1½ in thick max. (Impractical for large volumes) (Fig. 7)

5—Systems of criticality vessels

by water, a considerable improvement is obtained. Table V indicates that for Pu 239 a cylindrical vessel not exceeding 5·0 in. in diameter can be of infinite length and hence of infinite capacity. Likewise a slab type of vessel can in theory be made of any desired size provided that its width is not greater than 1·7 in.

Vessels may be designed by controlling the mass of product to be processed or by making them to 'ever-safe' standard by consideration of geometry. In the former type the vessels are made to a specific size so that a critical mass for the given conditions cannot be obtained, but considerable control of the process is necessary to ensure that the particular concentration of fissionable material does not increase above that for which the vessel size is safe. With the geometrically designed type, which will handle any concentration of product, plant supervision need not be so stringent. Figure 5 shows the breakdown of the various types of vessel, each of which has particular merit viewed either by its ease of manufacture, its economical use of plant space, or its functional reliability. The simplest form of construction is the mass control type in which a pot type of dissolver is surrounded by a steam heating jacket (Fig. 6). This presents no manufacturing difficulties and can be radiographically inspected to a



6—Pot type of construction

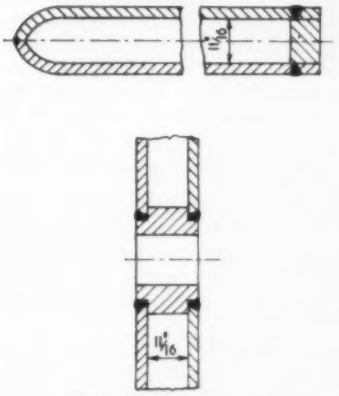
critical degree. Unfortunately, depending on the volume of material to be processed and its concentration, a large number of such vessels might be required which, coupled with the necessary supervision required for controlling the process, could be an uneconomical proposition.

The geometrically safe type, in which a pipe of restricted diameter is used, could in theory be made of infinite capacity. Naturally, a restriction must be placed on length or the pipe so disposed as to avoid inter-action between the various vessels. No manufacturing or inspection difficulties are presented but the plant space required for housing the assembly is a vital consideration.

Since full radiographic inspection can be used in both the foregoing types, they may be permitted to handle "active" solutions and are constructed from 18% Cr–13% Ni–Nb stainless steel.

An alternative method, in which two concentric cylinders form the containment, also offers a solution. Whilst manufacture is relatively straightforward, there are two disadvantages. Firstly, the fabricating cost is high considering the volume of material it can handle and, secondly, if a leak should occur on the inner vessel wall a critical mass might easily accumulate unless suitable precautions were to be taken. This further reflects on overall cost and does not make the design attractive.

A further method, which is frequently used for processing "inactive" material, is the slab tank. This type of vessel can be made geometrically safe for any condition but again has disadvantages. For the amount of material handled the cost of fabrication is high, and to maintain the width between fairly critical limits a careful manufacturing procedure must be followed. The difficulty of making, for example, vessels 4 ft deep, 8 ft long and only $\frac{3}{4}$ in. wide will be readily appreciated and, because of the support required between the vessel walls, welds free from crevices and capable of radiographic inspection are not practicable. It is, however, possible to make a continuous butt weld for the main containment by suitable forming of the plate edges (Fig. 7) but even so, radiography is impracticable because of lack of access for positioning the film. Control of penetration by argonarc techniques can be used and introscopic examination applied to ensure consistency of penetration. Figure 7 also shows the method adopted for supporting the wall of such vessels, and since the plant can be repaired the associated crevices are accepted.



7—*Slab dissolver details*

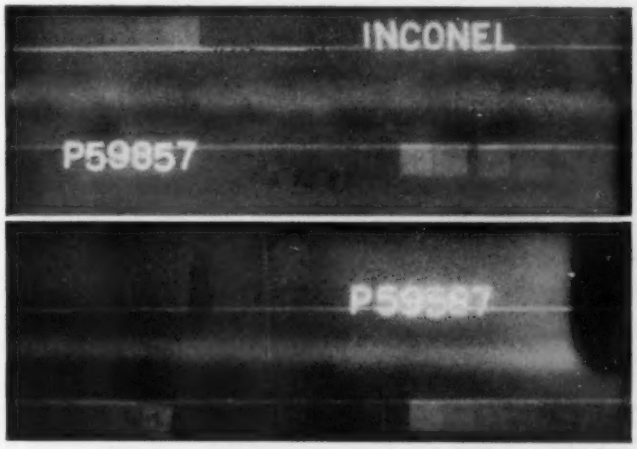
Chemical Plant Handling Hydrofluoric Acids

The information so far presented has dealt with the use of welding in plant designed for the processing of nuclear fuels after they have been irradiated. Since the efficiency of nuclear reactors is essentially dependent on the quality and consistency of nuclear fuel, high purity material is essential. In the chain of refining processes the useful properties of uranium-tetrafluoride and uranium-hexafluoride have played an important part, and the production of these compounds has led, in recent years, to the building of an extensive plant for chemical processing at high temperatures using hydrofluoric acids.[2] Since all concentrations of HF in both liquid and vapour states are involved, the nickel alloys Inconel and Monel have been extensively used, and the development of techniques to enable high quality welding to be consistently obtained has brought particular problems. These materials have, of course, been welded for many chemical plants satisfactorily for a number of years, but for the particular plant in question virtually defect-free welding as assessed by radiography to 1% sensitivity had never before been demanded on such a large scale.

The welding processes involved were all manually applied, following the same lines as those adopted for stainless steel vessels inasmuch as metal-arc welding was used in the construction of the vessels themselves and tungsten argonarc welding was applied exclusively on pipework.

Welding of Inconel

The main chemical reaction vessels operating at approximately 500°C. at a design pressure of 250 lb/sq.in. were constructed from Inconel rather than Monel because of mechanical considerations. These vessels are some 33 ft long, 3 ft 6 in. dia. reducing to 2 ft 6 in. dia. by means of a conical section, and $\frac{1}{2}$ in. thick.



8—*Radiographs of welds made with Inconel 132:* (a) *Electrode positive;* (b) *electrode negative*

Whilst reasonable success had been obtained on Monel of this thickness using manual metal-arc methods it was evident during the production of the initial test plates that a higher level of porosity was likely in Inconel. The application of Inconel 132 electrodes in the recommended manner resulted in a high level of porosity, which numerous variations of technique did not significantly reduce. However, when the electrodes were connected to the opposite pole of the d.c. supply (*i.e.*, to the negative) a considerable improvement was obtained (Figs. 8*a* and *b*). This improvement was rather surprising, since in a non-ferrous material it is unusual to find an electrode that

will run satisfactorily on either polarity and still more unusual to obtain better results in the manner now indicated. No tendency to slag entrapment or lack of fusion was found since arc stability was still good, although more skill was necessary when 6 s.w.g. electrodes were used. Before production was allowed to proceed, six procedure plates were prepared, some of which were curved to simulate circumferential seams, and on the satisfactory evidence from these plates vessel manufacture commenced.

It became apparent during construction that the weld quality was not consistent with that proved on the procedure plates, and a number of further investigations were undertaken. These investigations, covering variation in root gap, open circuit voltage of welding equipment, operator comfort, electrode size, interpass temperature, and overall cooling rate, did not reveal the reason for the inferior welds.

By this time supplies of a different electrode, of a type not manufactured since 1955, had become available. The objections raised by American users, which had led to its withdrawal, were said to be difficulty of slag removal and the requirement of an immediate re-bake to 250°C. for 2 hr before use. Neither of these two objections caused embarrassment to our programme since it was found essential to use grinding wheels to remove all traces of slag between runs with the Inconel 132 type (and in addition to remove surface porosity in each weld run), and re-baking of electrodes at 250°C. was already a requirement of the existing technique. These electrodes, designated BP24 type, produced welds of consistently good quality when run in the recommended manner with the electrode positive, and manufacture proceeded with relatively little trouble thereafter.

Welding of Monel

By far the largest number of plant items were constructed from Monel, ranging in thickness from $\frac{3}{16}$ in. to $\frac{1}{4}$ in. The design necessitated the construction of cylindrical vessels with dished ends. In some sizes, *i.e.*, 6 ft dia., the dished ends were cold formed and annealed, but in others hot-forming was necessary. The knuckle radius is subjected to a high tensile and bending stress during this forming operation, and considerable cracking occurred in the earlier pressings (Fig. 9).

9—Severe cracking in incorrectly pressed Monel dished end

During heating prior to hot forming, high sulphur and reducing atmospheres must be avoided to eliminate the possibility of embrittling grain boundary films, but the heat-treatment cycle must also be rigidly controlled. Prolonged heating above 1100°C. causes excessive grain coarsening and it is advisable to complete the forming operation above 850°C. When these precautions and the necessary degree of technical control were followed, satisfactory pressings were manufactured.

Early indications of the weld quality to be expected with metal-arc welding were obtained on $\frac{1}{2}$ in. thick material, and a high quality seemed assured. But though this was generally true for $\frac{1}{2}$ in. and $\frac{3}{8}$ in. thicknesses more difficulty was experienced on $\frac{1}{4}$ in. material, and when $\frac{3}{16}$ in. was attempted the trouble was acute. Whilst slag inclusions and lack of fusion were occasionally encountered, the large majority of defects were again pores and pipes. The original welded seams were often of high quality but required localized repairs to conform to specification. Extreme difficulty was experienced when making repairs, and only too often dimensional accuracy was lost owing to repeated attempts at repair and eventually weld cracking resulted. The onset of cracking could not be predicted, for seams offering similar restraint had sometimes cracked after two repairs whilst others underwent four or five operations without difficulty.

In the thinner sections tungsten argonarc methods using Monel 60 filler wire were tried. Whilst, in general better weld quality was obtained on the original weld, repair was even more hazardous since the slower process led to more rapid grain coarsening, and cracking occurred more frequently.

It should be appreciated that although the weld quality strived for was considerably higher than anything previously attempted, repair would still have been necessary under *any* acceptance code for certain defects and thus trouble still encountered in their rectification.

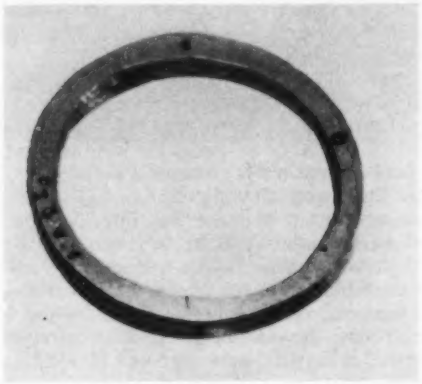
In spite of the most meticulous care, therefore, in adhering to cleanliness of parent plate and the welding materials, the use of highly-skilled operators and most careful supervision, the consistent reproduction of high quality welds does not appear to be assured using currently available welding materials.

The use of the inert-gas metal-arc systems was an obvious consideration, but on the evidence presented they offered no better guarantee of freedom from porosity. This applies equally well to nickel and Inconel, and it is understood that efforts are now being made to investigate thoroughly the mechanism of pore formation in the nickel alloys so that in future high quality welding as assessed by the best radiographic techniques available may be more readily assured.

Pipe welding

Interconnecting pipework in Monel, of sizes 1 in., 2 in., and 3 in. nominal bore pipe, with wall thickness of 0·080, 0·104, and 0·128 in. respectively, was extensively used. The positional welding of pipes on site, to give a sound weld, free from crevices and oxidation to the internal bead, brought particular problems. Control of penetration was obtained using tungsten argonarc techniques, and air was purged from the pipe interior by suitable admission of inert gas.

Because of the relatively thin wall of the pipes, argon-arc rather than metal-arc techniques, were also used for subsequent runs. It is well known that Monel cannot be gas welded (as is the case for stainless steel) because of a high incidence of porosity. The specially deoxidized filler wire, Monel 60, must thus be added in a manner to ensure that the net weld pool contains approximately 50% of filler metal. Failure to do this can result in major porosity, as can be seen from Fig. 10. This particular weld, however, indicates the desirability of radiographic examination, since the

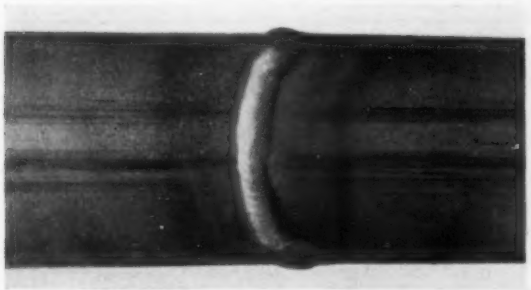


10—*Section through Monel pipe weld showing excessive porosity*

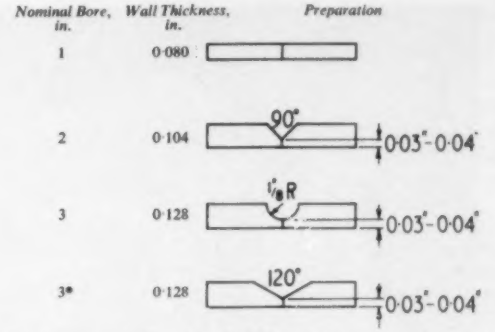
internal and external surfaces of the weld are entirely satisfactory. Butt welds in the three sizes mentioned were consistently produced to high quality (Fig. 11) using the preparations shown in Fig. 12 after welders had become accustomed to the manipulation required for the addition of sufficient filler metal. It is, nevertheless, important to have a tight fit of butting surfaces, otherwise inconsistencies can still arise.

Argon is commonly used to ensure a smooth oxidation-free internal bead surface but nitrogen was found to be equally effective. No indication of nitrogen pick-up could be detected in the welds, and mechanical and corrosion properties did not suffer. A tight butting joint face is even more necessary when nitrogen is used as purging gas, since any poor fit will lead to the entry of nitrogen to the arc atmosphere and so cause marked porosity even if the actual welding technique is performed in the approved manner.

It is also well known that the addition of controlled amounts of hydrogen to the argon shielding gas can



11—*Section of Monel pipe butt weld*



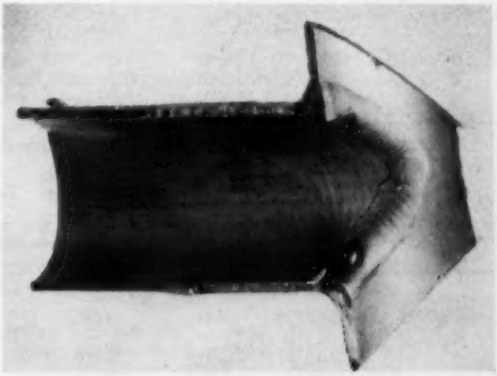
* For site prepared pipes where machining of J type preparation impossible

12—*Weld preparations for Monel pipe butt welds*

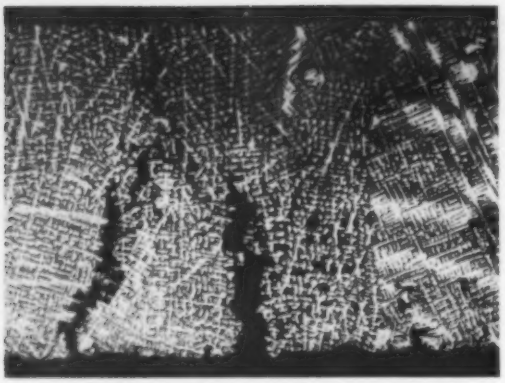
provide freedom from porosity when simple fusion of Monel is attempted. It was not thought suitable to apply it to this programme since ready-mixed cylinders of argon, plus 10% hydrogen, were not available. The apparatus that would have been necessary for controlling mixtures on site would have been of laboratory rather than production type, particularly since the flow of gases is small. It was therefore foreseen that, quite apart from the effect on the programme, any damage to such equipment might have had safety repercussions since explosive mixtures could be obtained.

Branch connections were a particular source of trouble, largely because of inconsistency of penetration and deep shrinkage craters (Fig. 13). The elimination of these particular faults demanded critical care in fitting the mating members after establishing suitable weld preparations, similar to that shown in Fig. 3*b*.

Because of initial difficulty in obtaining satisfactory branch welds, the 'pulled tee' method was investigated. It was found possible by cold forming to obtain a sufficient length of stub to permit orthodox butt welding without undue thinning of the stub pipe wall. Annealing of the cold-formed tee was done before welding the branch pipes. Although this method offered a considerable advantage in obviating the expensive and laborious hand grinding and fitting required by the forming method, it was felt that embarrassment to the production programme would



13—*Monel branch weld showing lack of penetration and shrinkage crater*



14—*Interdendritic attack on Monel weld*

result if repairs of pulled tee butt welds became necessary. Owing to the relatively short length of stub pipe possible, it would be almost impossible to rectify such a weld, if, for example, a lack of penetration had resulted, so that on a manifold containing anything up to a dozen such branches the hand-fitted weld preparation would still be required. By the time the technique of producing pulled tee connections had been established, considerably more success was being achieved on the hand-fitted method because of the close co-operation of fitter and welder. The rejection rate of welds made by this method is now less than 10%, even when a high radiographic standard is applied.

Metallurgical Studies Resulting from Operational Experience

During the initial operation of a prototype plant, using various concentrations of HF in the temperature range ambient to 400°C., a number of plant failures were experienced. During this period, the plant, although designed as a continuous process, was being operated on a batch system, and because of this and other modifications, it was not possible to maintain a low oxygen content.

As a result, corrosion failures occurred, and these were subjected to metallurgical examination. This revealed that in some cases the weld was preferentially attacked, but in other instances the weld was cathodic to the plate. Some welds contained a general precipitate, and these were always preferentially attacked. In one instance this precipitate was inter-dendritic and resulted in the attack shown in Fig. 14. Chemical analysis showed that the welds preferentially attacked always contained niobium (Table VI). In laboratory-welded samples, using Monel 60 filler wire and Monel 130 electrodes, it was not possible to produce this precipitate, even with gross misuse of welding techniques. All welds using Monel 140 electrode contained this precipitate.

Table VI

Composition limits for Monel plate and weld metals

Material	*Composition, wt.%*								
	C	*Mn*	*Fe*	*Si*	*Al*	*Ti*	*(Nb+Ta)*	*Ni*	*Cu*
Monel Plate	0·30	2·0	2·50	0·50	0·50	—	—	63·0–70·0	Remainder
Monel 60	0·15	1·0	2·50	1·50	1·25	1·5–3·0	—	62·0–69·0	,,
Monel 130	0·40	4·0	2·50	1·00	1·50	1·0	—	62·0–70·0	,,
Monel 140	0·15	2·5	2·50	1·25	0·75	1·5	3·0	62·0–70·0	,,

Table VII

Corrosion of Monel welds in 40% HF, 1% O_2 in hydrogen atmosphere at 70°C
(Attack on weld only, discounting attack on parent plate)

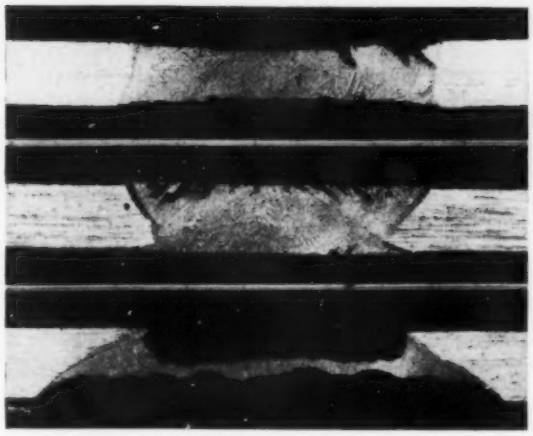
Weld Type		*Argonarc 60*		*Metal-arc 130**		*Metal-arc 140*		*Monel Plate*	
No. of Repairs	*Hours of Test*	*Liq.*	*Vap.*	*Liq.*	*Vap.*	*Liq.*	*Vap.*	*Liq.*	*Vap.*
				Penetration Rate, mm/yr					
0	1038	2·8	1·6	0·17	0·18	5·7	7·5	0·5	1·0
2	736	1·5	7·3	0·13	0·41	6·7	8·2		
4	322	5·0	12·0	0·20	0·78	11·0	14·0		

* Plate attacked preferentially to the weld. No signs of undercutting.

Table VIII

Difference in thickness between weld metal and parent plate after testing in 40% HF, 1% O_2 in hydrogen atmosphere at 70°C.

Weld Type		*Argonarc 60*		*Metal-arc 130*		*Metal-arc 140*	
No. of Repairs	*Hours of Test*	*Liq.*	*Vap.*	*Liq.*	*Vap.*	*Liq.*	*Vap.*
				Thickness difference, cm			
0	1038	0·012	0·001	−0·013	−0·006	0·040	0·050
2	736	0·004	0·003	−0·006	−0·005	0·080	0·029
4	322	0·025	0·014	−0·004	−0·002	0·090	0·030



15—*Weld appearance after corrosion test:* (a) *Monel 60;* (b) *Monel 130;* (c) *Monel 140* ×7

To investigate further this phenomenon, a comprehensive series of metallurgical and corrosion tests was initiated using Monel 60, Monel 130, and Monel 140 weld metals on both $\frac{3}{16}$ in. and $\frac{3}{8}$ in. plate. Composite plate and weld metal samples were treated in 40% HF at 70°C., with a gas flow of 1% oxygen in hydrogen continuously bubbled through the liquid phase at a rate of 300 mils/min. The results of the corrosion studies are shown in Table VII, and indicate that the rate of attack is dependent on the type of electrode used, increasing in severity from Monel 130 to Monel 60 and being most severe with Monel 140 electrodes. Figure 15 shows the comparative rates of attack with these three methods on unstressed samples treated for 1000 hr in liquid phase. It can be seen that for the Monel 140 there is a general corrosion attack, but marked fissuring is observed in the Monel 60 and 130 weld metals. This fissuring tends to follow the weld dendrites. In all these tests the Monel 130 weld metal was slightly cathodic to the plate. Table VIII shows the difference in thickness between the weld and the plate for the different electrodes after the same exposure.

It has been stated that it was necessary to carry out repeated repairs to obtain welds of a satisfactory quality. The rate of attack on the weld metal is however increased with increase in numbers of repairs. This is least marked for the Monel 130 electrodes. An applied stress equal in magnitude to the yield point did not materially affect the general corrosion rate as measured in the samples tested, but the fissuring referred to earlier was more marked in both the weld metal and the Monel plate.

Acknowledgments

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REFERENCES

1. I. H. Hogg: *Weld. Metal Fab.*, 1954, vol. 22, pp. 2–14.
2. K. M. Hill and H. Knott: "The Design of Plants for Handling Hydrofluoric Acid", Inst. Chemical Eng., March, 1960.

Welding of Precipitation-Hardening Corrosion-Resisting Steels

By J. I. Morley, A.MET. (Sheffield), F.I.M., *and J. A. McWilliam*, T.D., M.A.

The low carbon martensitic type and semi-austenitic type of precipitation-hardening stainless steels in the form of bar, centri-die spun castings, and sheet are described. Their compositions, heat-treatment, physical and mechanical properties, and weldability by metal-arc, argonarc, inert-gas metal-arc, and resistance welding processes are dealt with. The mechanical properties of various welds and the effect of post-weld heat-treatments are given. The application of these steels has solved a number of engineering problems.

Introduction

For many years there has been a demand for weldable corrosion-resisting steels with mechanical properties better than those obtainable on the 18% Cr–8% Ni types of steel. One of the earliest precipitation-hardening stainless steels, developed over 25 years ago, had the typical analysis:

C%	Si%	Mn%	Cr%	Ni%	Ti%	Al%
0·12	0·70	0·30	18·5	8·5	0·80	1·4

The normal heat treatment was A.C. 950°C., followed by A.C. 650°C. This gave a steel with a yield

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point of 35–40 tons/sq.in., a maximum stress of 45–50 tons/sq.in., and good elongation. Because of its high yield strength it was used primarily for steam turbine blading, and it had a resistance to corrosion similar to that of the 18% Cr–8% Ni steels.

More recently, Linnert* dealt particularly with the 17/4 PH, 17/7 PH, and 17/10 P steels. The difficulties encountered, and means of partially overcoming them were described. In 17/4 PH steel it is necessary to modify the analysis of the weld metal to obtain satisfactory properties after post-weld heat treatment.

The 17/7 PH steel contains about 1% Al, and is produced mostly as sheet or strip. In both inert-gas tungsten arc and consumable electrode processes a hazy film consisting mainly of aluminium oxide appears on the surface of the molten metal, and this makes satisfactory welding more difficult. For metal-arc coated electrode welding, 17/4 PH electrodes must be used with a special technique.

Steel 17/10 P contains about 0·25% P, and fusion welding is difficult owing to the great susceptibility to hot cracking of the weld bead.

British developments

The demand for high-tensile stainless steels that are readily (or easily) weldable has now been met by two steels which can be classified as (*A*) low carbon martensitic type, (*B*) semi-austenitic type. Typical compositions are given in Table I which shows that

Table I

Typical compositions of precipitation-hardening steels

Steel	*Analysis, %*							
	C	*Si*	*Mn*	*Cr*	*Ni*	*Mo*	*Cu*	*Nb*
(*A*) 520(B)	0·05	0·35	0·80	15·0	5·5	1·5	1·5	0·3
(*B*) 520(S)	0·05	0·50	1·00	16·0	5·5	2·0	2·0	—

both types contain chromium, nickel, copper, and molybdenum. The balance of composition is carefully controlled to give components which are readily weldable and which also respond to heat-treatment to give the required mechanical properties.

Low Carbon Martensitic Steel (Type A)

This is made in the form of bar, forgings, seamless tube, wire, and both centrispun and static castings. The physical properties are given in Table II, and the mechanical properties in Table III. The coefficient of linear thermal expansion is similar to that of mild steel, *i.e.*, only about two-thirds that of 18/8 steel. This feature is a help in avoiding distortion during welding.

Mechanical properties of metal-arc and argonarc welded 520(B) steel

This steel is now being welded without difficulty using the metal-arc, argonarc, and inert-gas metal-arc methods. After considerable research, suitable coated electrodes have been developed, and for argonarc and

* G. E. LINNERT: 1956 Adams Lecture, *Welding J.*, 1957, vol. 36, pp. 9–27.

Table II

Physical properties of 520(B) steel

Structure	Martensitic
Melting Point (approx.), °C.	1435
Specific Gravity	7·80 (=486 lb/cu.ft)
Modulus of Elasticity, tons/sq.in.	13,000
Thermal Conductivity, c.g.s. units	At 50°C. 0·038
	At 450°C. 0·055
Electrical Resistivity, $\mu\Omega$/cm	At 20°C. 85
Coefficient of Thermal Expansion	
20°/100°C.	0·000012
20°/300°C.	0·000013
20°/500°C.	0·000013
Magnetic Properties	Magnetic
(Induction B for H=250)	10,500
Permeability	110

Table III

Heat-treatment and typical mechanical properties of 520(B) steel

Heat treatment

(*a*) Overaged 620°C. (Condition as supplied for special requirements)
A.C. 1000°C.+2 hr 750°C., A.C.+1 hr 620°C., A.C.

(*b*) Overaged 560°C. (Standard condition as supplied)
A.C. 1000°C.+2 hr 750°C., A.C.+2 hr 560°C., A.C.

(*c*) Precipitation-hardened
A.C. 1000°C.+4 hr 450°C., A.C.

Typical mechanical properties

	Overaged 620°C. (*a*)	Overaged 560°C. (*b*)	Precipitation hardened (*c*)
0·1% Proof Stress, tons/sq.in.	30	56	68
Maximum Stress, tons/sq.in.	60	65	85
Elongation, %	25	25	15
Reduction in Area, %	60	60	50
Hardness, D.P.N.	290	320	400
Fatigue Limit, tons/sq.in. (10^8 cycles unbroken)	±38	±36	
Izod Impact, ft-lb at 20°C.	80	75	25
ft-lb at −78°C.	75	70	15

Note: (*c*) Bar supplied A.C. 1000°C. (320 D.P.N.). Precipitation hardened to 400 D.P.N. after rough machining.

Table IV

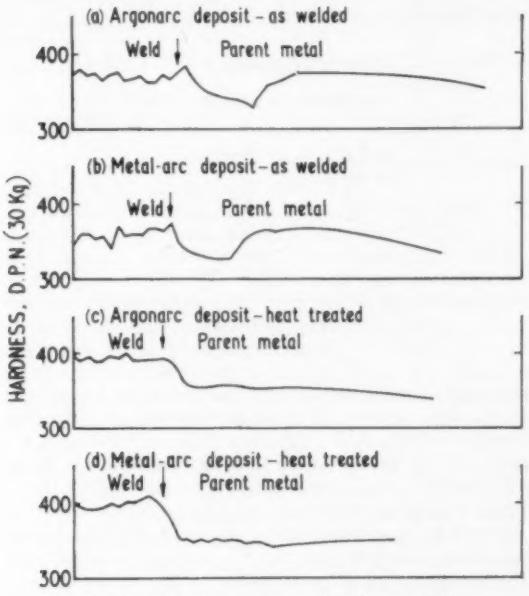
Compositions of bar, wire, and deposit

	Analysis, %			
	Cast 08780 Bar	*Cast 45064 12 s.w.g wire*	*Cast 45064 after deposition*	*PH2 electrodes after deposition*
C	0·05	0·05	0·05	0·08
Si	0·28	0·41	0·35	0·23
Mn	0·70	0·69	0·65	0·96
S	—	0·009	—	0·007
P	—	0·014	—	0·018
Cr	13·88	14·54	14·43	14·14
Ni	5·51	5·67	5·60	5·51
Mo	1·75	1·66	1·62	1·85
Cu	1·63	1·80	1·73	1·80
Nb	0·38	0·46	0·31	0·61

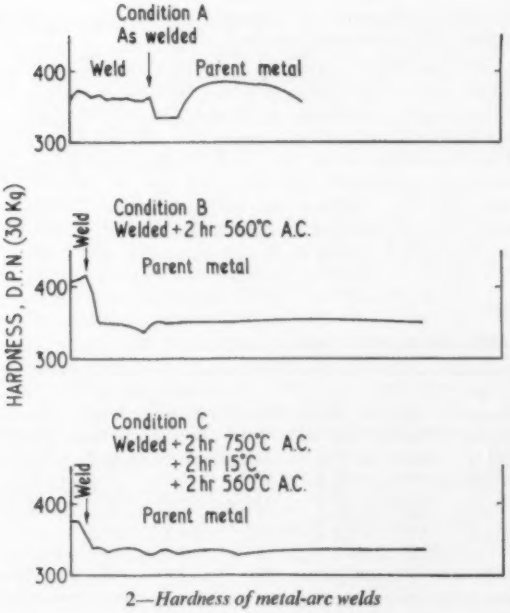
shielded inert-gas metal-arc welding the analysis of the filler wire is similar to that of the parent metal.

Table IV shows the analyses of the test bar, the 12 s.w.g. filler wire for argonarc welding before and after deposition, and also the deposit from the PH2 electrodes used for the metal-arc welds.

Samples of $1\frac{1}{8}$ in. dia. hot rolled bar, Cast No. 08780, of the composition indicated by Table IV, were prepared with a 90° double-V for butt welding after a heat-treatment of 30 min. 1050°C., A.C.+4 hr 750°C., A.C.



1—*Hardness of argonarc and metal-arc welds*



2—*Hardness of metal-arc welds*

The welds were made (*a*) by argonarc (d.c., electrode –ve) using 12 s.w.g. wire of similar analysis to the bar, and (*b*) by metal-arc (d.c., electrode +ve) using PH2 electrodes.

A hardness traverse was carried out on each weld in the as-welded condition. The results are shown in Fig. 1. Both welds were then given the heat-treatment: 4 hr 750°C., A.C.+2 hr 15°C. max.+1 hr 550°C., A.C.

Hardness traverses were again carried out in this condition in both welds. These results are also shown in Fig. 1.

Tensile tests were machined with the weld at mid-gauge length and the results are shown in Table V.

Effect of post-weld heat-treatment of metal-arc welded 520(B) steel on sub-zero, room temperature, and elevated temperature properties

Two samples of 5×1 in. flat bar from Cast 48298 were prepared with a 90° double-V after a heat-treatment of 30 min. 1050°C., A.C.+2 hr 750°C., A.C.

The analysis of Cast 48298 was as follows:

C%	0·06	Cr%	14·62
Si%	0·30	Ni%	5·57
Mn%	0·69	Mo%	1·68
S%	0·009	Cu%	1·93
P%	0·019	Nb%	0·32

The samples were welded using PH2 electrodes.

Hardness traverses and room-temperature tensile tests were carried out (*a*) as-welded; (*b*) after 2 hr at 560°C., A.C.; and (*c*) after 2 hr at 750°C., A.C.+2 hr at 15°C. max.+2 hr at 560°C., A.C. Tensile tests at

Table V

Tensile tests

	Argonarc Weld	*Metal-arc Weld*
0·05% Proof Stress, tons/sq.in.	58·2	58·7
0·1% " " "	61·0	61·3
0·2% " " "	62·6	63·0
0·5% " " "	64·0	65·0
Maximum Stress, tons/sq.in.	66·2	66·6
Elongation, %	17½	17
Reduction in Area, %	61	61

Both samples fractured within the parent metal

−78°C., and at 300°C. were also carried out after treatments (*b*) and (*c*). The hardness traverses are shown in Fig. 2 and the tensile tests results are given in Table VI.

The hardness traverses and tensile tests show no significant difference between the metal-arc and argonarc welded samples. It is interesting to note that the high-temperature heat-affected zone in 520(B) steel is not hardened, and may be actually slightly softer than the unheated metal. A zone of hardening does occur where the metal is heated to a somewhat lower temperature, presumably within the range of 400°–550°C. where ageing occurs. The hardening in this zone is not severe, being not greater than 390 D.P.N. in the hardest sample. After the post-weld heat-treatment the weld metal is between 40 and 60 D.P.N. units

Table VI

Tensile tests on metal-arc welds showing effect of post-weld treatments

	(*a*)	(*b*)	(*b*)	(*b*)	(*c*)	(*c*)	(*c*)
Testing temperature, °C.	R.T.	−78	R.T.	300	−78	R.T.	300
0·05% Proof Stress, tons/sq.in.	40·0	53·1	50·5	43·2	57·3	51·4	44·5
0·1% " " "	44·8	59·0	55·0	47·0	60·7	55·0	47·0
0·2% " " "	51·0	63·2	58·0	50·0	63·0	58·0	49·5
0·5% " " "	—	67·0	61·1	52·0	65·3	61·1	51·1
Maximum Stress, tons/sq.in.	55·4	75·8	65·4	54·8	72·3	64·0	52·9
Elongation, %	1½	26·5	21½	13½	25·5	22½	16
Reduction in Area, %	1½	62·7	64	48	65·3	66½	50½

Sample (*a*) broke short in weld; all other fractures in parent metal

harder than the parent metal and this means that, unless a sample breaks short, fracture always occurs within the parent metal. The tensile test in the as-welded condition did break short with a fracture within the weld. A repeat test broke in the weld. These tensile tests show the desirability of post-weld heat-treatment.

Fatigue tests on 520(B) weld metal deposited by the argonarc process

Fatigue tests were made on weld pads using wire with the following composition:

C%	0·05	Ni%	5·67
Si%	0·41	Mo%	1·66
Mn%	0·69	Cu%	1·80
Cr%	14·54	Nb%	0·46

The deposited material was treated for 4 hr at 750°C.+1 hr at 550°C. The Wöhler fatigue test results are given in Table VII. They indicate a fatigue limit of ±34 tons/sq.in.

Table VII

Fatigue tests on argonarc welds

Stress, tons/sq.in.	*Reversals*
±42	242,300
±38	25,724,700
±36	47,290,000
±34	256,589,200 UB
±30	110,281,900 UB

UB = Unbroken

Mechanical properties of metal-arc welded 520(B) centri-die spun castings

Large numbers of centrifugally spun castings in dies are made in many corrosion- and heat-resisting steels. This process has been applied very successfully to 520(B) steel.

The centri-die castings were given a heat-treatment of 3 hr 1050°C., A.C. to room temperature; 4 hr 750°C., A.C. to room temperature; 4 hr 550°–560°C., A.C.

The castings were then machined to 12 in. o.d.× 8 in. i.d.×7 in. long. The weld edge was a J preparation from one side only owing to the small diameter. The welding was done using PH2 coated electrodes. Tensile tests were carried out on the parent metal, on the weld metal, and on test pieces taken across the welds. The tests were done (*a*) as-welded; (*b*) after 1 hr at 550°C., A.C.; (*c*) after 2 hr at 750°C., A.C., held for 24 hr at room temperature, and 1 hr at 550°–560°C., A.C.; and (*d*) 12 hr at 550°C., A.C. Table VIII gives the results of these tests.

It will be noted that the mechanical properties have been much improved by the post-weld heat-treatment. The treatment of 12 hr at 550°C., A.C. can be used as a stress-relieving treatment after welding, for it does not impair the high-tensile properties.

Mechanical properties of argonarc and inert-gas metal-arc welded 520(B) centri-die cast rings

The machined centri-die castings were 11¾ in. o.d.× 7¾ in. i.d.×12 in. long. The first run was a sealing run using argon backing, followed by fifteen runs of argonarc deposit using $\frac{1}{16}$ in. dia. 520(B) filler wire. The remainder of the weld was made in 26 runs by the inert-gas metal-arc process using $\frac{1}{16}$ in. dia. 520(B) wire for the consumable electrode. The centrispun rings were rotated at a suitable speed during the welding operation. After each run the weldment was well

Table VIII

Tensile tests on centri-die cast 520(B) steel metal-arc welds

	1 *As Welded*	*2* *Treatment b*	*3* *As Welded*	*4* *Treatment b*	*5* *As Welded*	*6* *As Welded*	*7* *Treatment b*	*8* *Treatment b*	*9* *Treatment c*	*10* *Treatment d*
0·05% Proof Stress, tons/sq.in.	50·5	50·5	23·3	34·4	41·0	37·9	44·0	41·5	51·0	43·1
0·1% " " "	54·2	54·0	25·0	38·2	44·1	41·2	48·7	46·3	53·5	48·8
0·2% " " "	57·2	57·0	26·8	42·1	47·3	44·2	53·0	50·6	54·9	52·9
0·5% " " "	60·7	60·3	29·2	47·5	50·7	49·0	57·2	55·3	57·0	57·0
Maximum Stress, tons/sq.in.	66·6	64·8	65·8	68·4	57·0	59·8	63·3	64·4	60·2	63·2
Elongation, %	15	15	6	7	3½	4	13	4	16	14
Reduction in Area, %	22	35	7½	7½	3	7	40	6	45	43

Table IX

Tensile tests of inert-gas metal-arc welds on 520(B) steel centri-die castings

	Parent Metal	*Tensile Across Weld*				*Weld Metal only*
	*Treatment**	*1*	*2*	*2*	*3*	*3*
0·5% Proof Stress, tons/sq.in.	58·4	34·0	54·5	51·2	45·0	54·0
Maximum Stress, tons/sq.in.	63·2	64·2	58·0	57·6	63·0	62·6
Elongation, %	15	10	9	8	7	10·5
Reduction in Area, %	36	26	38	36	27	35

* (1) As-welded
(2) 3 hr at 750°C., 24 hr at room temperature, 12 hr at 550°C., A.C.
(3) 12 hr at 550°C., A.C.
All test pieces across welds fractured in parent material

cleaned using a grinding wheel, wire brush, or rotary wire brush to remove any oxide film.

The results of the tensile tests, given in Table IX, show that joints made using initial runs by the argon-arc process followed by runs from consumable electrodes of the same analysis as the parent metal have given very satisfactory results. It has been clearly established that post-weld heat-treatment is most desirable so as to restore the 0·5% proof strength. Other tests have confirmed that better results were obtained with the 750°–550°C. treatment than with the 550°C. treatment only.

Welds to other steels

Centri-die cast 520(B) was argonarc welded without difficulty to mild steel, using 520(B) filler wire. Tensile tests across the weld broke in the mild steel away from the weld. A metal-arc weld to 18/8/Ti steel, using 18/8/Nb type electrodes gave no trouble, and tensile test fractures were in the 18/8/Ti steel away from the weld.

Welding conditions

Throughout, in the fusion welding of 520(B) steel, the welding conditions such as current, argon flow, etc., were similar to those used for 18/8 steels. The advantage of the material over 18/8 steels lies in its lower coefficient of expansion, which lessens the chance of distortion.

Semi-Austenitic Steels (Type S)

Those precipitation-hardening stainless steels that are classed as semi-austenitic, the second of the two groups under consideration, are characterized by their response to heat-treatment, particularly in that quick cooling from 1000°C. or above will give a low yield point austenitic condition. This circumstance makes the semi-austenitic steels especially suitable for cold rolling into sheet and strip and allows fairly severe forming operations to be carried out on the flat rolled products. Components so produced may be hardened by a two-stage heat-treatment, comprising primary hardening (which induces a transformation to martensite with an accompanying expansion), followed by precipitation-hardening. The combination of these heat-treatments provides structures of high and uniform strength in all parts and in all directions irrespective of the amount of deformation involved in the forming operations. Given the correct weld metal composition the welds and heat-affected zones can also be made to respond to similar hardening treatments.

For applications where the total amount of deformation during forming is very small, less than about 6%, the steels are sometimes supplied in a higher yield point martensitic condition, obtained by partial softening at a temperature below 1000°C., commonly 870°C. in the case of 520(S), a typical steel of its type. This variant of the supplier's heat-treatment is useful in that it considerably simplifies the hardening and descaling procedures to be carried out subsequent to forming; the volume change on hardening is very slight and good mechanical properties can be obtained by the use of a single heat-treatment at 550°C.

Hardening procedure

Unwelded condition

The composition and typical mechanical properties of 520(S) in the austenitic or martensitic conditions as supplied, and after the appropriate hardening heat-treatments, are shown in Tables X and XI respectively.

It will be noted from Table XI that a sub-zero primary hardening treatment at −70°C. can sometimes be used as an alternative to the 750°C. treatment. In both cases an expansion of 0·3–0·4% is involved on account of the martensite transformation, and due allowance must be made for this, either in design or by correcting parts to size after transformation. As already mentioned this difficulty does not arise where the steel is supplied in the A.C. 870°C. martensitic condition but, in many instances, the forming is too severe for the 870°C. treatment and the steel must be used in the A.C. 1050°C. austenitic condition.

Weldments (*Steel supplied in the austenitic condition*)

Because of the volume expansion accompanying the transformation of austenite to martensite it is always better to apply the martensite transformation treatment to individual pressings or sections before they are assembled for welding, so as to reduce the risk of serious distortion of the finished component.

For similar reasons, when welding pressings of 520(S), formed in the austenitic condition, to flanges, rings or castings of 520(B) steel, it is again advisable to apply the martensite transformation treatment to the pressings before their assembly for welding. In some cases a sub-zero treatment may be used as an alternative to the 750°C. treatment.

It will have been noted from the response of the

Table X

Compositions of 520(S) sheet

Cast No.	*Sheet Thickness, s.w.g.*	*Analysis, %*						
		C	*Si*	*Mn*	*Cr*	*Ni*	*Mo*	*Cu*
47821	18	0·06	0·41	1·26	15·68	5·49	1·68	2·00
51457	18	0·05	0·41	1·26	15·24	5·68	1·97	1·95
50541	10	0·05	0·29	1·28	15·82	5·62	1·92	1·98

Table XI

Mechanical properties of 520(S) 18 s.w.g. sheet

Cast No.	*Direction of Test Piece**	*Heat Treatment*	*Proof Stress 0·1%*	*Proof Stress 0·2%*	*Max. Stress,*	*Elong. on 2 in., %*	*Elong., % (4√A)*
				tons/sq.in.			
47821	T	A.C. 1050°C. (austenitic as supplied)	15·7	18·2	53·9	30	—
	T	A.C. 1050°C. + 2 hr 750°C., A.C. + 2 hr 550°C., A.C.	66·3	67·9	70·3	12	—
	T	A.C. 1050°C. + 6 hr −70°C. + 2 hr 550°C., A.C.	65·7	74·6	81·2	13	—
51457	L	A.C. 870°C. (martensitic as supplied)	26·7	27·5	69·5	11	—
	L	A.C. 870°C. + 4 hr 0°C. + 2 hr 550°C.	64·2	68·0	72·1	15	25
	L	As above. Tested at 400°C.	47·4	51·1	59·9	6½	16

* T = Transverse to rolling direction; L = Parallel to rolling direction

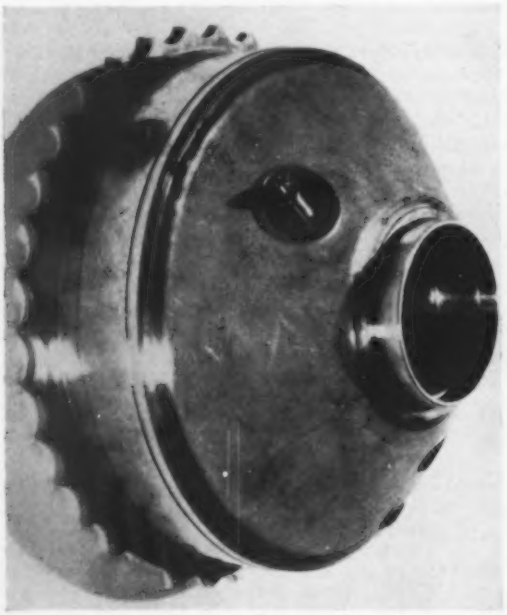
Table XII

Tensile tests on argonarc welded 520(S) 18 s.w.g. sheet

Heat Treatment	*Sheet Thickness, s.w.g.*	*Proof Stress 0·1%*	*Proof Stress 0·2%*	*Max Stress,*	*Elong. on 2 in., %*	*Cast No.*
			tons/sq.in.			
A.C. 1050°C. (Austenitic) + 2 hr 750°C. + Weld + 2 hr 750°C. + 2 hr 550°C.	18	56·2	57·2	60·8	7	47821
As above but *unwelded*	18	58·6	60·4	64·6	13½	47821
A.C. 1050°C. (Austenitic) + 2 hr 750°C. + Weld	18	53·3	55·8	59·2	10	47821
+ 2 hr 700°C. + 2 hr 550°C.	10	50·5	53·9	62·2	14½	50541
As above but *unwelded*	18	55·4	57·9	63·8	13½	47821
	10	51·1	55·9	62·7	18	50541
A.C. 1050°C. (Austenitic) + 2 hr 750°C. + Weld	18	54·1	57·7	65·8	11	47821
+ 6 hr −70°C. + 2 hr 550°C.	10	50·1	53·9	61·7	12½	50541
As above but *unwelded*	18	65·0	67·5	70·8	9	47821
	10	61·4	64·3	66·8	14	50541

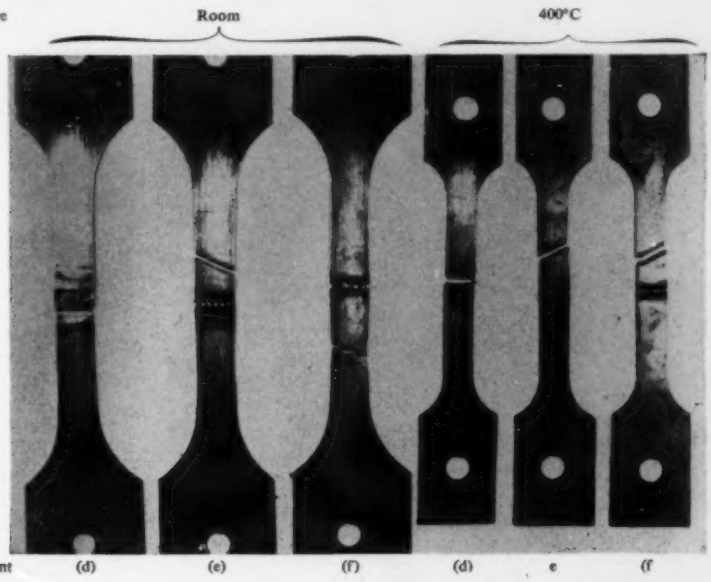
semi-austenitic steels to softening treatment of 1000°C. and above that austenite will also be retained in 520(S) steel in a narrow zone adjacent to the weld where the metal is cooled quickly from welding heat. This does not occur with the martensitic 520(B) steel.

An additional martensitic transformation treatment applied after welding will transform these narrow austenitic zones adjacent to the weld beads, a procedure which does not seem to cause distortion, perhaps because the very localized expansion at the weld is offset to some extent by the relief of residual weld tension stresses.



3—Welded gear box casing

4—Pressing formed in the austenitic condition for gear box



5—*Tensile tests of argonarc welds*

The following tests were carried out as an illustration of the effects of various post-weld heat-treatment cycles on the mechanical properties of welds in 520(S) sheet and strip, and to show how sub-zero post-weld treatments may be used to ease descaling problems.

Table XII gives the results of tensile tests on 18 s.w.g. sheet specimens of Cast 47821, butt welded by a single argonarc run using 16 s.w.g. 520(B) filler wire. The sheet specimens for welding were prepared from A.C. 1050°C. austenitic material, and were transformed to the martensitic condition by a 2 hr treatment at 750°C. before welding. The welds were in the middle of the gauge length, and all beads were dressed by grinding.

The following post-weld treatments were carried out on welded specimens and on unwelded blanks for comparison:

(*a*) 2 hr at 750°C., A.C.+2 hr at 550°C., A.C.
(*b*) 2 hr at 700°C., A.C.+2 hr at 550°C., A.C.
(*c*) 6 hr at −78°C.+2 hr at 550°C., A.C.

As usual, a period of not less than 24 hr at room temperature was allowed between the 750° or 700°C. treatments and the 550°C. treatments, so as to ensure completion of the martensite transformation.

In all cases fracture occurred in the parent metal at a position $\frac{3}{8}$–$\frac{1}{2}$ in. outside the weld joint line, *i.e.*, the weld was stronger than the parent metal.

As shown in Table XII the welded test pieces, after double post-weld heat-treatment, gave values of 0·1% proof stress in tests across the weld joints at least 95% of those for corresponding unwelded tests, thus illustrating the effective hardening of the weld zones. When sub-zero post-weld treatment is used the recovery in strength of the weld is relatively less complete, but it is still possible to achieve 0·1% proof stress values of about 50 tons/sq.in. This sub-zero post-weld treatment plus overageing at 550°C. is often preferred because descaling is easier. Any oxidation that occurs at 550°C. is not difficult to remove if the parts are thoroughly degreased before heat-treatment.

The gear box casings illustrated in Fig. 3 were produced from 520(B) forgings and bar and 520(S) rings, argonarc welded with 520(B) filler wire. The individual 520(S) pressings shown in Fig. 4 were transformed at 750°C. and descaled before assembly for welding. After welding a sub-zero treatment at −65°C. was applied, followed by a 560°C. precipitation treatment.

Weldments (520(*S*) *supplied in the martensitic condition*)

Weld specimens were prepared from 18 s.w.g. sheet of Cast 51457 using a single-run argonarc technique and 520(B) filler wire. In this case the weld beads were not dressed before testing. Tensile tests were carried out at room temperature and at 400°C., with the welds at mid gauge length, after the following post-weld treatments:

(*d*) Weld+4 hr at 0°C.+2 hr at 550°C.
(*e*) Weld+4 hr at −70°C.+2 hr at 550°C.
(*f*) Weld+2 hr at 750°C., A.C.+4 hr at 0°C.+2 hr at 550°C.

The tensile test pieces are shown in Fig. 5.

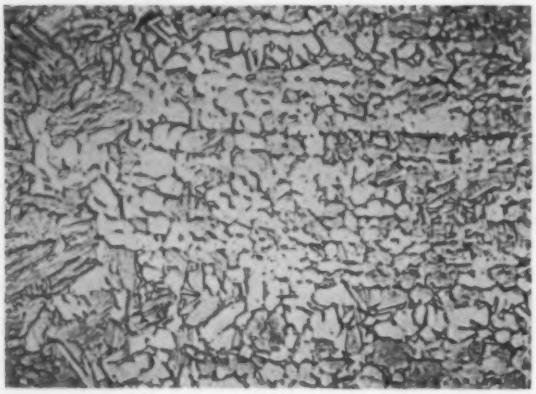
The high-temperature heat-affected zone of the sheet in the as-welded condition is shown in Fig. 6. The absence of grain growth and freedom from excessive amounts of delta ferrite will be noted.

The mechanical test results are given in Table XIII. These indicate that the hardness of the high-temperature heat-affected zone beside the weld is not fully recovered by means of the 4 hr 0°C.+2 hr 550°C. post-weld treatment, notwithstanding that this treatment works well on steel supplied partially softened at 870°C., as shown in Table XI. The greater austenite stability of the weld heat-affected zone is due to the solution of carbides during welding. It will be noted from Table XIII that sub-zero cooling to −70°C.,

Table XIII

Argonarc welds on 18 s.w.g. 520(S) sheets (Cast 51457)

	Post-Weld Treatment	*Testing Temp., °C.*	*Proof Stress, 0·05%*	*0·1%*	*0·2% tons/sq.in.*	*Max. Stress,*	*Elong. on 2 in., %*	*Elong., % ($4\sqrt{A}$)*
(*d*)	4 hr 0°C. + 2 hr 550°C., A.C.	20	23·5	26·7	30·9	66·1	11	15
(*e*)	4 hr −70°C. + 2 hr 550°C., A.C.	20	47·1	51·9	56·9	71·9	13	22
(*f*)	2 hr 750°C., A.C. + 4 hr 0°C. + 2 hr 550°C., A.C.	20	67·0	69·2	70·1	72·1	11½	25
	As (*d*)	400	22·3	26·2	29·8	39·1	3	12
	As (*e*)	400	38·6	44·5	49·0	55·8	7	16
	As (*f*)	400	50·5	52·6	54·2	58·4	5½	16



6—*Hight-temperature heat-affected zone, as-welded* ×500

followed by the 550°C. overageing treatment, does give very satisfactory strength across the welds. As a matter of interest still higher proof stress values may be obtained by a triple post-weld treatment involving consecutive stages at 750°C., 0°C., and 550°C., but it is considered that the −70°C. treatment followed by 550°C. will be the more attractive post-weld hardening treatment.

It is worthy of note that this simple post-weld treatment is not applicable to all precipitation-hardening steels of the semi-austenitic class, for most of these do not appear to have the particular composition balance that allows 520(S) to respond in this way. Their weld heat-affected zones have inherently greater austenite stability, so that more complex triple- or quadruple-stage post-weld treatments are recommended by the manufacturers concerned.

Electric resistance welding

Very good spot and seam welds are being made on various thicknesses of sheet. As with 18/8 steels, scrupulous cleanliness, thermionic control of current and times, and the use of hard copper alloy electrodes are essential. The optimum welding conditions, and the effect of post-weld heat-treatment are being investigated by a B.W.R.A. Committee under the chairmanship of one of the authors.

Summary

The authors hope they have made clear the great possibilities that these steels have in the solving of difficult engineering problems, particularly where the welding of high-tensile steels is concerned. These steels have been particularly applied in making aircraft structures, aero engines, and plant for the production of power. Welding engineers have been impressed with the ease with which welding has been carried out on steels of high tensile and fatigue strength.

Acknowledgments

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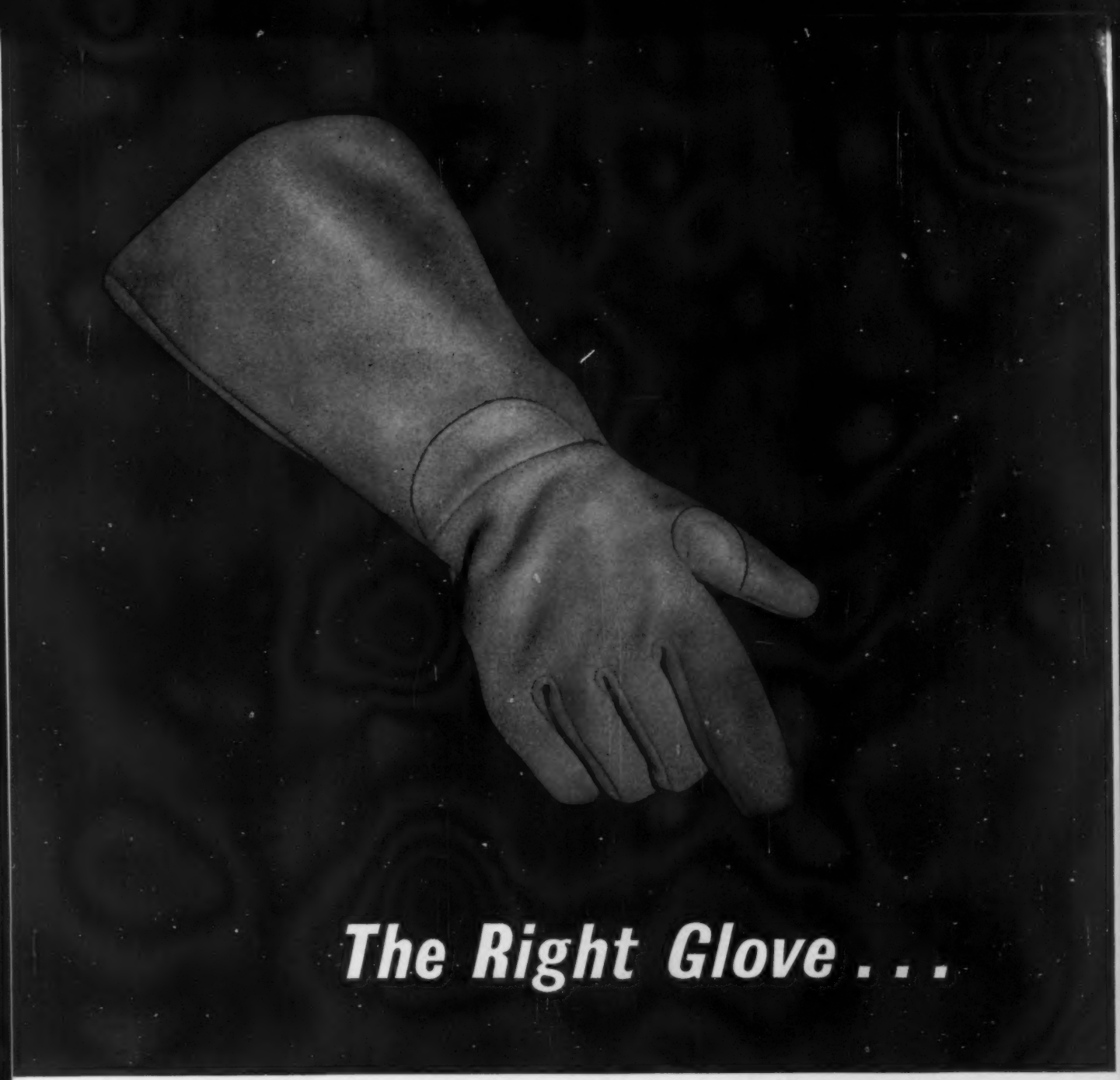

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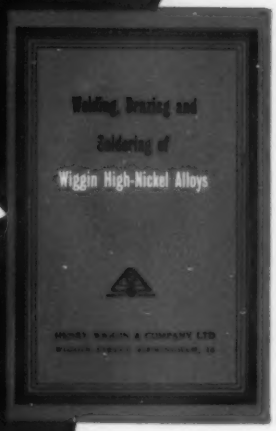

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NEWS
and Announcements

News of the Institute and Branches
B.W.R.A. · Other Societies ·
and Industry

INSTITUTE ACTIVITIES

AUTUMN MEETING 1960

The Metallurgy of Welding and Brazing

The Autumn Meeting of the Institute will be held at 54 Princes Gate, London S.W.7, from **1st to 3rd November 1960.**

The proceedings will include the presentation of the Presidential Address, the Annual Dinner, and the presentation and discussion of technical papers on the metallurgy of welding and brazing.

Members of the Institution of Metallurgists will take part in a joint discussion on "The Role of the Metallurgist in Fabrication involving Welding".

The programme of the meeting is as follows:

Tuesday, 1st November

6.0 p.m.—Tea, coffee.
6.30 p.m.—Presidential Address, by E. Fuchs, M.A., A.M.I.Mech.E.
7.15–8.15 p.m.—Opening Reception.

Wednesday, 2nd November

9.30 a.m.–**12.30** p.m.—First Technical Session for the discussion of the papers:
"*Use of Welding in Chemical Plants in the U.K.A.E.A.*" by F. S. Dickinson and B. Watkins.
"*Welding Problems Associated with Nuclear Fuel Elements*" by A. F. Taylor.
"*Welding Metallurgy of the Nimonic Alloys*" by J. Hinde and D. R. Thorneycroft.
"*Welding of Precipitation-Hardening and Corrosion-Resisting Steels*" by J. I. Morley and J. A. McWilliam.
"*Whither Electrode Design*?" by I. C. Fitch.

2.30–5.30 p.m.—Second Technical Session for the discussion of the papers:
"*Cracking Tests for Assessing Weldability*" by J. C. Borland.
"*Cracking in Welded Joints of 18/12 Austenitic Steel in C.E.G.B. Power Stations*" by F. E. Asbury, B. Mitchell, and L. H. Toft.
"*Distribution of Phosphorus and Sulphur in Fully Austenitic Stainless Steel Welds*" by S. M. Makin, C. B. Alcock, D. R. Arkell, and P. C. L. Pfeil.
"*Hot Cracking in Mild and Alloy Steels*" by W. K. B. Marshall.
"*High-Frequency Induction Brazing of Small Components in Argon Streams*" by P. M. Bartle and J. G. Young.

6.30 p.m.—Joint Meeting with the Institution of Metallurgists: Discussion opened by J. F. Lancaster and and H. E. Dixon on "*The Role of the Metallurgist in Fabrication involving Welding*".

Thursday, 3rd November

9.30 a.m.–**12.30** p.m.—Report on "*Welding Research and Practice in the U.S.S.R.*" by members of the Institute team which visited the U.S.S.R. in September.

7.15 for **7.45** p.m.—Annual Dinner at the Park Lane Hotel, Piccadilly, London W.1.

Applications for Dinner Tickets should be made to the Secretary by 27th October (latest)—price £3 including cocktails. Members of the Institute are entitled to one ticket at £2 10*s*. 0*d*. on personal application.

Tickets for the Reception are also obtainable from the Secretary (price £1: but those enrolling for the Autumn Meeting will be able to attend free of charge.)

The papers for discussion are published in this (October) issue of *B.W.J.* with the exception of that by Mr. Marshall (July, 1960) and that by Mr. Asbury and others (November, 1960).

Christmas Lecture to Young People

The Annual Christmas Lecture to Young People will be given by Professor J. G. Ball at the Institute on Thursday, **5th January,** 1961, at 11.0 a.m.

Admission will be by ticket, and tickets will be available for members at the end of November.

Postgraduate Course in Welding

The Ministry of Education has agreed to offer at the College of Aeronautics, Cranfield, beginning in the Autumn of 1961, a postgraduate course in welding technology leading to the grant of a Diploma in Advanced Engineering.

This decision was reached at the end of August, when it became certain that the minimum number of students for the first year's course would be forthcoming from industry, as a result of promises obtained by the Institute of Welding.

The President has set up a special committee to foster the postgraduate course and to ensure the support of industry for it and for improvements in welding education generally. The members of the committee are as follows:

Mr. E. Fuchs (President of the Institute)
Professor J. G. Ball (Imperial College of Science and Technology)
Mr. F. Caunce (H.M.I., Ministry of Education)
Dr. E. F. Gibbs (Bristol University)
Mr. A. G. Grant (Managing Director, Whessoe Ltd.)
Dr. N. Gross (Managing Director of Quasi-Arc Ltd., and Chairman of the Executive Committee of the Institute)
Professor A. J. Murphy (Prinicipal of the College of Aeronautics)
Mr. E. Seymour-Semper (Managing Director of Hancock & Co. (Engineers) Ltd., and Past-President of the Institute)
Dr. R. Weck (Director of Research of the British Welding Research Association)
Mr. R. E. G. Weddell (Director of W. G. Allen & Sons (Tipton) Ltd., and a Past-President of the Institute)

At its first meeting the committee examined a draft syllabus of the course, received the promises of support already

mentioned, and agreed upon measures to make the course known to industry. Full particulars will soon be widely distributed to members of the Institute and the B.W.R.A., and to industry generally.

NEWS OF MEMBERS

Obituary

The Council records with regret the deaths of the following members:

Mr. G. Johnson, attached to the West of Scotland Branch (elected 1944) in September 1959.

Mr. N. A. Tucker of Johnson. Matthey & Co. Ltd., an active and much valued member of the Institute, who died very suddenly on 14th August 1960. Mr. Tucker was a British delegate on the IIW Commission III, Resistance Welding, on which subject he was a recognized authority. He will be much missed in the organization of the Institute's technical activities.

A. F. Taylor

D. R. Thorneycroft

B. Watkins

CONTRIBUTORS TO THE JOURNAL

P. M. Bartle, L.I.M., is a member of the Non-Ferrous Metallurgy Department of the British Welding Research Association, and is concerned particularly with brazing and with the welding of copper.

He was educated at Acton County Grammar School, and later at Wandsworth Technical College and Battersea College of Technology, as a part-time student. He has recently passed the examination for Licentiateship of the Institution of Metallurgists.

Mr. Bartle spent two years with the British Non-Ferrous Metals Research Association before taking up his present appointment in 1956.

F. S. Dickinson, A.M.I.Mech.E., served an engineering apprenticeship with Metropolitan Vickers Electrical Co. Ltd. (now A.E.I. Manchester Ltd.), subsequently joining the Welding Engineering Department in 1945, and being transferred to the main fabricating department in 1948.

In 1953 he joined the Department of Atomic Energy (Production) of the M.O.S. and advised design departments, construction staff and the inspectorate on welding techniques.

He is now Senior Welding Engineer at the Culcheth Laboratories of the United Kingdom Atomic Energy Authority and is responsible for providing manufacturing and design data for the wide range of fabricated plant constructed for the United Kingdom Atomic Energy Authority.

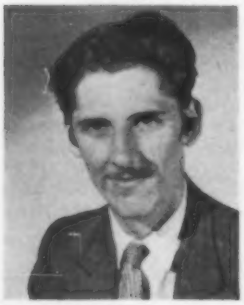
J. Hinde, F.I.M., M.Inst.W., on the staff of the Development and Research Department of The Mond Nickel Co. Ltd., received his metallurgical education at the Wolverhampton and Staffordshire Technical College. In 1929 he joined Thompson Brothers (Bilston) Ltd., and was later appointed metallurgist to the Company. In 1936 he became a metallurgist in the Engine Division of the Bristol Aeroplane Co. Ltd., and four years later he was appointed Chief Metallurgist at the Accrington Engine Factory of the Company. In 1945 he was recalled to Bristol to take up the post of Development Metallurgist. He joined The Mond Nickel Co. Ltd. in 1953 to take charge of the development activities involved in the joining of nickel-containing materials. In 1959 he was appointed Manager of the Non-Ferrous Division of the Development and Research Department; that Division is concerned however, with the development of the welding attributes of all the nickel-containing materials.

J. A. McWilliam, T.D., M.A., is Head of the Research Liaison Department of Firth-Vickers Stainless Steels Ltd., Sheffield. He was educated at Glasgow Academy, St. John's College, Cambridge, and at Sheffield University. He joined the staff of the Brown-Firth Research Laboratories in 1924, and from 1925 to 1929 he was in charge of the Pyrometric Laboratories. At that time he also undertook research on the welding of new steels.

From 1929 to 1932 Mr. McWilliam visited Australia, New Zealand, Japan, China, Ceylon, South Africa, Rhodesia, and Canada to give technical advice on the manipulation and application of steels produced by Thos. Firth and Sons Ltd., and Thos. Firth and John Brown Ltd. On the formation of Firth-Vickers Stainless Steels Ltd. in 1934, he was transferred to that Company, and in 1938–39 he again visited Canada and the U.S.A. to study methods of manufacture and fabrication of stainless steels and aircraft and aero engines.

Mr. McWilliam served as Lt. Colonel in command of the 46th Divisional R.E. from 1939 to 1941, and was with the B.E.F. in France in 1940. He later undertook work on the increasing use of welded heat-resisting steel fabrication for aircraft and aero engines. He was awarded the Territorial Decoration in 1945. For the paper "*The welding of stainless steels*" he was given the Hatfield Memorial Prize of the Sheffield Metallurgical Association in 1946.

After the war he resumed visits to Europe in connection with the welded fabrication of corrosion- and heat-resisting steels, in addition to similar work at home. In 1954 he visited South Africa and read a paper to the South African Institution of Welding on "*The welding of corrosion- and heat-resisting steels*", for which he was awarded the Harvey Shacklock Gold Medal of the Institution. He has given numerous lectures and papers on the manipulation of stainless steels, including a lecture to the Institution of Engineers in Denmark.



A. M. Bartle

F. S. Dickinson

J. A. McWilliam

Mr. McWilliam is a Vice-President of the Sheffield Society of Engineers and Metallurgists, and is past Chairman of the Sheffield and District Branch of the Institute of Welding.

A. F. Taylor, B.Sc., A.I.M., was born in 1924. He was educated at the George Dixon Grammar School, Birmingham, and later at Birmingham University, where he obtained an Honours Degree in Industrial Metallurgy in 1950.

During the war Mr. Taylor served with the R.A.F. in Coastal Command. After taking his degree he joined the Research and Development Branch of the U.K.A.E.A. at Springfield Works. He worked initially on the development of methods for canning fuel elements, and is now responsible for the development of welding techniques for fuel element applications.

Dennis R. Thorneycroft, B.Sc., A.I.M., M.Inst.W., Welding Development Officer with The Mond Nickel Company Ltd., London, was appointed to the senior research staff of the Birmingham Laboratory of The Mond Nickel Company Ltd. in 1944. In subsequent years he gained research experience in several fields of metallurgy, including that of the transformation characteristics of cast and wrought alloy steels.

From 1953 he was engaged on research in the ferrous and non-ferrous field of welding metallurgy, and in 1956 was appointed Section Head of the Welding and Non-ferrous Department. In the Autumn of 1959 he was transferred to development in the Development and Research Department at London, where he took up his present position with the Company.

B. Watkins, M.Sc., A.I.M., graduated in Metallurgy at the University College of Swansea and was subsequently awarded the degree of M.Sc. in 1948. He was then employed at the Department of Research and Technical Development of Stewart & Lloyd Ltd., Corby, until he joined the Culcheth Laboratories of the United Kingdom Atomic Energy Authority in 1956, where he now leads a team of Metallurgists and Welding Engineers giving an advisory service on the selection of materials, fabrication and construction of reactors and associated chemical plant.

BRANCH NEWS

Sessional Programmes

Birmingham

14th Oct.—Chairman's Address "*The other applications of oxygen*", by K. H. Purdy
11th Nov.—"*Resistance welding as a production process*" by C. A. Burton
1st Dec.—Annual Dinner
9th Dec.—Lecturettes: "*Fine wire welding*" by D. B. Tait; "*Electro-slag welding*" by C. A. Burden; "*Plasma jets*" by R. Cresswell
13th Jan.—"*Designing for brazing*" by N. H. Jones
17th Feb.—Lecturettes: "*Electron beam welding*" by L. N. Sayer; "*High-frequency welding*" by J. B. P. Williamson; "*Ultrasonic welding*" by J. W. Menter
17th Mar.—"*Economic aspects of various fusion welding processes*" by W. D. Waller
22nd Mar.—Visit to Hereford Works of Henry Wiggin & Co. Ltd.
14th April—Annual General Meeting and Technical Films

Except for the works visit, meetings will be held at the Grand Hotel, Birmingham, starting at 7.30 p.m.

East Midlands

21st Sept.—Visit to Stanton Ironworks
11th Oct.—"*A practical approach to the problem of distortion*" by J. S. Waring. Nottingham
15th Nov.—"*Pipe line welding*" by R. J. Wright. Derby
13th Dec.—"*Electro-slag welding*" by W. K. B. Marshall. Nottingham
18th Jan. Loughborough. Not yet finalised
8th Feb.—"*Economic aspects of various fusion welding processes*" by W. D. Waller. Nottingham
4th April—Annual General Meeting and Films. Nottingham

East of Scotland

29th Sept.—Visit to Henry Balfour & Co. Ltd., Leven, Fife
19th Oct.—Chairman's Address
16th Nov.—Films
18th Jan.—"*Pipe line welding*" by R. J. Wright
15th Feb.—"*Recent advances in electric welding*" by A. Bean
20th Feb.—"*Welding and allied processes*". Films and discussion. Joint meeting with the Institution of Engineering Inspection, The Royal British Hotel, Dundee, 7.30 p.m.
15th Mar.—"*Electric pre-heating and stress relieving*" by R. McGlashan
12th April—Annual General Meeting

Unless otherwise stated or advised all the above meetings are held at 25 Charlotte Square, Edinburgh, and commence at 7.30 p.m.

Leeds

22nd Sept.—Ladies Night
5th Oct.—"*Practical approach to distortion problems*" by J. S. Waring
25th Oct.—"*Welding and the draughtsman*" by H. B. Merriman
16th Nov.—"*Practical welding of large fabrications*" by C. Spencer
29th Nov.—To be arranged (Wakefield)
8th/9th Dec.—Annual Dinner, Hotel Metropole, Leeds
15th Dec.—"*Brazing and copper welding*" by G. F. Charge
10th Feb.—Dinner Dance, Mansion Hotel, Roundhay
March.—Works Visit, Allerton Bywater Colliery
11th April—Annual General Meeting.

The above lectures will be held at the Hotel Metropole, Leeds, commencing at 7.30 p.m.

Liverpool

15th Sept.—"*History of the Manchester Ship Canal*", with film, "*Port of Manchester*", by E. Greenwood.
24th Sept.—Ladies' Day (Ship Canal, embark Pier Head, Liverpool, 10.30 a.m.)
11th Oct.—Visit to Brymbo Steel Works (Wrexham, 3 p.m.)
11th Oct.—"*Welding of Cast Iron.*" Demonstration by V. J. Swallows, Lecture by W. H. Holland (Wrexham Technical College, 7 p.m.)
10th Nov.—"*Weld Radiography*", by Dr. L. Mullins (Liverpool Central Library, 7.15 p.m.)
13th Dec.—"*The Practice of Metallizing.*" Demonstration by E. W. Whitelock, Lecture by H. F. Smith.
10th Jan.—"*Prefabricated Welding of Ships' Structures*", by J. W. Day.
14th Feb.—"*Iron Powder Electrodes*", by A. B. Fieldhouse.
14th Mar.—"*Welding and the Draughtsman*", by H. B. Merriman.
11th Apr.—23rd Annual General Meeting and Film Show.
21st Apr.—17th Annual Dinner to entertain the Lecturers (Victoria Hotel, New Brighton)

Except where otherwise indicated, meetings are held at the College of Technology, Byrom Street, starting at 7.15 p.m.

Manchester

Session 1960–61

An extremely interesting and varied programme of talks has been arranged for the Winter session of 1960–61. The committee look forward to good attendance and support from members and friends old and new.

This is a particularly noteworthy year for the Branch, for it is honoured that

one of its longstanding members, Mr. E. Fuchs, M.A., has been elected President of the Institute for 1960–61.

A.C.M.

5th Oct.—"*The selection of welding processes*" by B. K. Barber
19th Oct.—"*Mastering imperfections by a code of good welding practice*" by Colin Spencer, Bolton Municipal Technical College, Bolton, 7.15 p.m.
2nd Nov.—"*A survey of fusion welding developments*" by A. A. Smith
7th Dec.—"*Automatic welding*" by J. A. Lucey
4th Jan.—"*Pipeline welding*" by R. J. Wright
1st Feb.—"*Electro-slag welding*" by A. M. Horsfield
1st Mar.—"*Methods adopted by a large user when purchasing welded equipment*" by E. Fuchs and W. Ashworth
6th Mar.—Annual Dinner, Grand Hotel, Manchester.
5th April—Annual General Meeting and film shows

With the exception shown, meetings will be held in Reynolds Hall, College of Science and Technology, Manchester, at 7.15 p.m.

N.E. Tees-side

8th Sept.—Works Visit to I.C.I. Central Workshops, Billingham
10th Oct.—Open Discussion
23rd Nov.—"*Some notes on shipyard re-organization*" by R. Ibeson, (Joint with N.E. Coast Eng. & Ship.).
12th Dec.—"*Design, fabrication, and assembly of walking dragline excavators*" by C. McL. Cameron.
9th Jan.—"*Weld interpretation by radiographic methods*" by T. W. Brown
13th Mar.—"*Ferrous welding metallurgy*" by T. E. M. Jones
10th April—Annual Meeting and Chairman's Address

N.E. Tyneside

14th Oct.—"*Developments in shipbuilding steels*" by E. E. Clark
3rd Nov.—"*Some aspects of CO_2 welding*" by F. Collins and G. Blackhurst
1st Dec.—"*Electro-slag process*" by D. J. W. Boag
3rd Dec.—Branch Dinner
5th Jan.—"*Some special applications of welding in steam, gas turbine, and nuclear power plants*" by Dr. J. M. Robertson
2nd Feb.—"*Gas cutting*" by G. Sims-Davies
2nd Mar.—"*The work of B.W.R.A.*" by H. F. Tremlett
4th Mar.—Visit to Clarke, Chapman & Co. Ltd., Gateshead
13th Apr.—"*Computer controlled cutting*" by R. Sillifant

Preston

12th Oct.—Chairman's Address and Films, Harris Technical College, Preston, 7.15 p.m.
9th Nov.—"*Economics of machine tool purchase*" by J. Borsay, Harris Technical College, Preston, 7.15 p.m.
5th Dec.—"*Pipe line welding*" by R. J. Wright, Lancaster Technical College, 7.15 p.m.
18th Jan.—"*Fabrication and brazing of copper pipes*" by G. F. Charge, Municipal College, Burnley, 7.15 p.m.
24th Feb.—"*Future of gas shielded welding*" by A. A. Smith, Technical College, Barrow, 7.30 p.m.
8th Mar.—"*Recent developments in U.S.S.R.*" by Dr. D. S. Galloway, Harris Technical College, Preston, 7.15 p.m.

Sheffield

26th Sept.—Visit to Thorncliffe Works of Newton Chambers & Co. Ltd., Chapeltown, followed by lecture by W. J. Colton
10th Oct.—Visit to Sheffield College of Technology, Department of Engineering, followed by talk by H. W. Hodson
7th Nov.—"*Welding for the construction of weldments for low temperature service*" by R. E. Lismer
12th Dec.—"*British Railways welding of railway rolling stock*" by G. Walton. Joint meeting with the Institution of Production Engineers, Sheffield section
9th Jan.—Annual Branch Dinner—Royal Victoria Hotel
16th Jan.—"*Use of welding in chemical plants in the U.K.A.E.A.*" by F. S. Dickinson. Joint meeting with the Rotherham College of Technology Engineering Society
13th Feb.—"*Electro-slag welding*" by W. K. B. Marshall
13th Mar.—"*Heat-affected zone cracking in austenitic chromium–nickel steels*" by H. F. Tremlett

Meetings, other than the Joint ones, are held at the Grand Hotel, Sheffield, commencing at 7.0 p.m.

Southern Counties

20th Oct.—"*Welding of austenitic and corrosion resisting steels*" by J. A. McWilliam
17th Nov.—"*Pipe line welding*" by R. J. Wright
8th Dec.—"*Welding of motor car bodies*' by J. H. J. Church
19th Jan.—Meeting with the Naval Architects and Marine Engineers
16th Feb.—To be arranged
16th Mar.—"*Lead burning, etc.*" by L. B. Smith
13th April—Annual General Meeting and technical film

South London

Medway Section

2nd Nov.—Demonstration — Electro-slag welding, at Burnett & Rolfe Ltd., The Esplanade, Rochester, 7.30 p.m.
22nd Feb.—"*Pipe line welding*". Joint meeting with Institute of Petroleum, King's Head Hotel, Rochester, 7.30 p.m.
22nd Mar.—"*Brains Trust*", Sun Hotel, Chatham, 7.30 p.m.
10th April—Annual General Meeting, Sun Hotel, Chatham, 7.30 p.m.

South Western

10th Oct.—"*Arc welding power sources*" by J. A. Lucey, Radiant House, Bristol, 7.15 p.m.
7th Nov.—Film Show—Steel Production—School of Technology, Gloucester, 7.15 p.m.
5th Dec.—Welding Forum, Radiant House, Bristol, 7.15 p.m.
9th Jan.—"*Future of gas shielded welding*" by A. A. Smith, Radiant House, Bristol, 7.15 p.m.
6th Feb.—"*Structural design for welding*", by R. J. Fowler, Stothert & Pitt's Canteen, Bath, 7.15 p.m.
6th Mar.—"*Non-destructive testing*" by Mr. Gibbs, Radiant House, Bristol, 7.15 p.m.

West of Scotland

19th Oct.—"*Weld radiography*" by E. J. Grimwade
15th Nov.—"*Universal beams—after two years*" by A. W. Turner. Joint meeting with the Institute of Structural Engineers
21st Dec.—"*Electro-slag welding*" by A. M. Horsfield
18th Jan.—"*Welding and design in the fabrication of high strength steels*" by L. H. Liston
15th Feb.—"*Further thoughts on shipyard re-organization*" by D. B. Kimber
15th Mar.—"*Electric pre-heating and stress relieving*" by R. McGlashan
30th Mar.—Visit to the Fairfield Shipbuilding & Engineering Co. Ltd., Glasgow
19th April—Annual General Meeting and Film Night

Wolverhampton

19th Oct.—Chairman's Address by E. J. Mitchell, Old Wulfrunians Club
16th Nov.—"*Weld inspection*" by A. H. Goodger
7th Dec.—"*Welding and physical metallurgy*" by T. Fullwood
18th Jan.—"*Construction and erection of Maidenhead by-pass Thames bridge*" by J. S. Allen
15th Feb.—"*Welding of austenitic to ferritic steels*" by F. S. Dickinson
15th Mar.—"*The prospect for gas-shielded welding*" by A. A. Smith
March or **April**—Works visit to be arranged
14th April—16th Annual Dinner and Ladies' Night, Wulfrun Hall
17th April—Annual General Meeting
May or **June**—12th Annual Meeting with Liverpool Branch

NAMES AND ADDRESSES OF BRANCH SECRETARIES

For the benefit of members who may wish to attend meetings at branches other than their own, or to make contact with other members we give the following list of Honorary Secretaries and their addresses:

Birmingham: J. R. MERTHER, 9 Brook Street, West Bromwich, Staffs

Eastern Counties: J. A. EDWARDS, Corner Ways, Fingringhoe Road, Abberton, Nr. Colchester, Essex

East Midlands: K. HOUGHTON, 20 Shirley Road, Leicester

East of Scotland: R. D. BERRY, 13 Craigs Gardens, Edinburgh 12

Indian: B. N. MAJUMDAR, c/o Association of Engineers, 24 Netaji Subhas Road, Calcutta 1

Leeds and District: M. W. PARKINSON, 1106 Leeds Road, Woodkirk, Dewsbury, Yorkshire

Liverpool: H. R. COX, 21 Oaklands Drive, Bebington, Cheshire

Manchester: A. C. WHITE, 78a Sandy Lane, Prestwich, Manchester

North Eastern (Tees-side): F. G. BATCHELOR, 5 Dionysia Road, North Ormesby, Middlesbrough

North Eastern (Tyneside): T. S. NICOL, Bolbec Hall, Newcastle upon Tyne 1

North London: J. F. GIBBS, 927 Great Cambridge Road, Enfield, Middlesex

North London (Slough Section): J. F. GALLAGHER, 3 Hazel Grove, Staines, Middx.

Preston: R. ROBINSON, Daneham, Pope Lane, New Longton, Preston, Lancs

Sheffield: G. W. CRAGG, Highcroft, 22 Lilly Hall Road, Maltby, Rotherham, Yorks

Southern Counties: J. H. GILLESPIE, 12 Burlington Road, Southampton, Hants

South London: J. P. MOORE, 110 Kingston Road, Teddington, Middlesex

South London (Medway Section): P. MURRELL, 21 Wayville Road, Dartford, Kent

South Wales; G. BERRIDGE, 7 Alison Court, Newton, Porthcawl, S. Wales

South Western: G. W. RIGBY, 10 Roundmoor Close, Saltford, Nr. Bristol, Somerset

West of Scotland: H. H. MACKINTOSH, 144 St. Vincent Street, Glasgow C.2

Wolverhampton: J. W. GETHIN, c/o Old Park Engineering Ltd., Holly Hall, Dudley, Worcs.

NEWS FROM INDUSTRY

Soviet Welding Delegation Visits U.K.

At the time of going to press, arrangements had been made, under the auspices of the British Electrical and Allied Manufacturers' Association, for a team of Russian welding experts to visit British welding firms and organizations from 16th September to 7th October 1960.

The Russian team is to be headed by B. E. Paton, Director of the Soviet Institute of Welding, and other members will be: V. P. Sokolov, Chief Welding Engineer of Soviet welding plant; V. P. Andreev, Chief of the Welding Department of the Soviet Research Institute; M. I. Baranov, Engineer in welding applications in the automobile industry; and L. B. Kolesmikov, interpreter.

A report of the delegation's visit will be given in a later issue of *B.W.J.*

Steels for Reactor Pressure Circuits

The Iron and Steel Institute is to organize a symposium on this subject, as part of the activities of the British Nuclear Energy Conference.

The symposium will be held from 30th November to 2nd December in the Hoare Memorial Hall, Church House, Westminster.

The provisional programme includes discussion of papers under the following headings:

Session I—High-temperature properties

Session II—Corrosion

Session III—Fabrication aspects

Session IV—Irradiation effects

Session V—Steels for future reactors.

Full details of the symposium may be obtained from the Secretary of the Iron and Steel Institute, 4 Grosvenor Gardens, London S.W.1.

NEW PLANT AND EQUIPMENT

Capacitor discharge controller

A stored-energy controller (Types CD 1 and CD 2) for supplying precise amounts of power to the welding electrodes, regardless of mains fluctuations, is now being produced by Hirst Electronics Ltd. The unit operates on normal wiring installations, having its own built-in stabilized d.c. supply, with a maximum alternating current demand of 1 amp.

The controller can deal with extremely short weld times—15 millisec max., and 3 millisec min. with quick recovery periods.

Small bevel cutter

A small version of the B.O.G. 'Alyn' bevel cutter has been developed for use by the Central Electricity Generating Board. The machine was first used to prepare the ends of 2⅝ in. dia. tubes for replacing damaged sections in the Bromborough Power Station boilers.

The models now in production incorporate rotary gas valves and a method of micro-setting for the position of the cut.

Electrode dryer

One of the few entirely British stands at the 12th Liège International Fair, in June, was that of the Spooner Dryer and Engineering Co. Ltd., of Ilkley. Their main display was a prototype of a new automatic welding electrode drying machine, shown in the accompanying illustration.

High-speed cutting nozzles

An addition to the 'Saffire' range of equipment has been made by British Oxygen Gases Ltd. by the introduction of new high-speed nozzles that have been developed for machine cutting.

The cutting orifices are of convergent-divergent form, to make the oxygen leave the nozzle at high speed in a parallel stream. This results in high linear cutting speeds—45 ft/hr on 7 in. plate, or 100 ft/hr on 1 in. plate.

Zn-Al metal spray coating

At the Institute's Spring Meeting, reference was made to development work on the application of Zn–Al powder mixtures and alloys for the prevention of corrosion of iron and steel.

F. W. Berk & Co. Ltd. (Coating Division) have now announced the production of 'Berkalloy' Zn-Al metal spray coating in powder form for application by flame spraying equipment.

The coating has universal corrosion prevention properties, and extensive tests have shown that the new coating gives equal protection under alkaline and acidic conditions of corrosion.

Automatic vertical welding

In the August issue of *B.W.J.* (p. 591) a brief description was given of the Rockweld Circomatic seam welding machine. At the time this machine was being demonstrated at the Liège International Fair a further development, the Comatic machine, was also shown in prototype form.

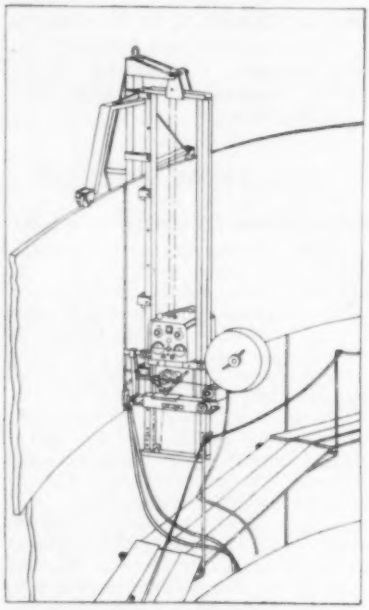
Although the full technical details of this machine are not yet available, the following brief description may be of interest.

The Comatic welder has been designed specifically for the automatic welding of the vertical seams of large storage tanks; in effect, it complements the Circomatic horizontal seam welder. The basic operational principles of the machine combine those of the Rockweld-Vus Vertomatic electro-slag welding equipment and the Comet CO_2 process. Thus the high deposition rates of CO_2 welding have been combined with the method of weld formation, by the use of moving water-cooled copper shoes, that is a feature of electro-slag welding.

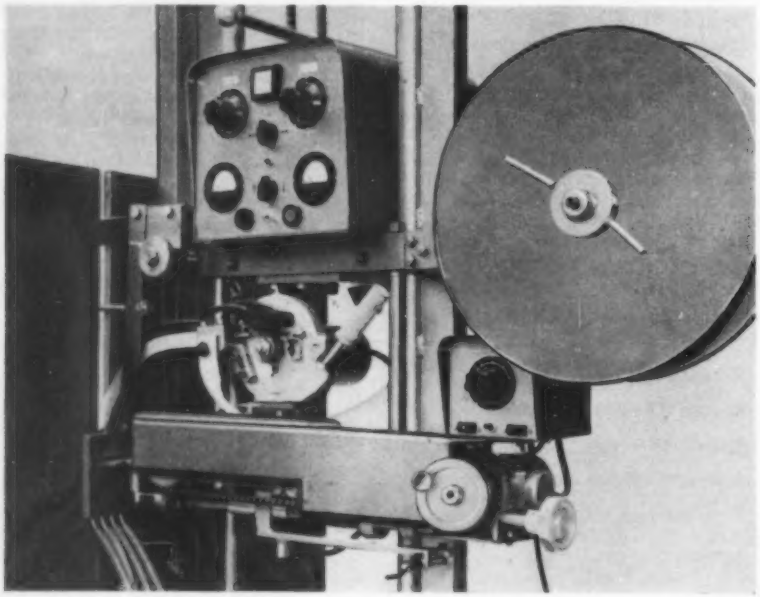
The new equipment can be used for welding plates from $\frac{1}{2}$ to $2\frac{1}{2}$ in. thick. This is a particularly useful feature, for the electro-slag process is generally not suitable for plates below about $1\frac{1}{4}$ in. thick. Welding speeds are comparable with those of normal CO_2 equipment but are much faster than those obtainable with the electro-slag process; for example, a joint between $\frac{3}{4}$ in. thick plates can be welded at a rate of 15 ft/hr.

The illustration shows the head of the machine, which is mounted with all controls and wire drum on a twin-track vertical frame. This frame in turn is attached to, and supported by, the shell of the storage tank. For the thinner range of plates the arc is kept central in a small gap between the square-edged plates. This provides sufficient wall penetration. For thicker materials the filler wire is made to oscillate across a wider gap, in the same way as in the electro-slag process.

The power supply to the equipment is a standard drooping-characteristic generator, or a transformer-rectifier, rated at 750 amp continuous duty, and fitted with current control only, for the welding head is equipped with arc-voltage control.



Comatic vertical welder



CORRECTION

The date of publication of the Sir William Larke Medal paper (News Section, August 1960 issue, p. 532, foot of 3rd column) was inadvertently given as 1956. This should have been May 1958.

DIARY

5th Oct.—Leeds—"*Practical approach to distortion problems*" by J. S. Waring (Hotel Metropole, Leeds, 7.30 p.m.
Manchester—"*The selection of welding processes*" by B. K. Barber (Reynolds Hall, College of Science and Technology, 7.15 p.m.)

10th Oct.—N.E. Tees-side—Open discussion
Sheffield—Visit to Sheffield College of Technology, Dept. of Engineering, followed by talk by H. W. Hodson
South Western—"*Arc welding power sources*" by J. A. Lucey (Radiant House, Bristol, 7.15 p.m.)

10th–11th Oct.—School of Welding Technology—Course D13/2—Residual stresses and stress relief

11th Oct.—East Midlands—"*A practical approach to the problem of distortion*" by J. S. Waring (Nottingham)
Liverpool—Visit to Brymbo Steel Works (Wrexham, 3.0 p.m.); Demonstration of welding of cast iron, by V. J. Swallows (Wrexham Technical College, 7.0 p.m.)

12th Oct.—Preston—Chairman's Address and films (Harris Technical College, 7.15 p.m.)

12th–14th Oct.—School of Welding Technology—Course D12/2 — Practical control of distortion

14th Oct.—N.E. Tyneside—"*Developments in shipbuilding steels*" by E. E. Clark

14th Oct.—Birmingham — Chairman's Address "*The other applications of oxygen*" by K. H. Purdy (Grand Hotel, Birmingham, 7.30 p.m.)

19th Oct.—East of Scotland—Chairman's Address (25 Charlotte Square, Edinburgh, 7.30 p.m.)
Manchester — "*Mastering imperfections by a code of good welding practice*" by C. Spencer (Reynolds Hall, College of Science & Technology, 7.15 p.m.)
West of Scotland — "*Weld radiography*" by E. J. Grimwade
Wolverhampton—Chairman's Address by E. J. Mitchell (Old Wulfrunians Club)

20th Oct.—Southern Counties—"*Welding of austenitic and corrosion resisting steels*" by J. A. McWilliam
Eastern Counties.—"*Fabrication of Plastics*" by D. Shorten (Ipswich.)

24th–27th Oct.—School of Welding Technology—Course D18/1—Metal spraying

Current WELDING LITERATURE

Book Reviews

Additions to the Institute Library

Trade Publications

CONTENTS OF PERIODICALS RECEIVED

This section is intended to give a survey of the current welding literature received by the Institute of Welding Library. The contents lists are not exhaustive; only the main articles in welding journals are listed, and reprints from other journals and short notes are generally excluded. In addition, welding articles from other periodicals are listed. Abstracts of welding literature are given in the Bibliographical Bulletin of Welding and Allied Processes, *published by the International Institute of Welding, and details of this may be obtained from the Secretary of the Institute of Welding.*

Welding Journals

Journal of the Japan Welding Society, 1960, vol. 29, April

Observations of studies on the weldability of structural, quenched and tempered steels; Part 3, T. Yoshida and others (3–14)

Studies on porosity in welded joints; Report 1, Y. Ando and others (30–36)

Some basic experiments of acetylene purifier; Report 2, I. Ueda and H. Shinotani (37–39)

Study on soft soldering; Report 2, T. Kawasaki (40–43)

Study on soft soldering; Report 3, T. Kawasaki (44–47)

A proposal to find out easily arc stability of welding electrode, T. Yoshida and others (48–55)

On carbon arc blasting; Report 1, M. Nakatsukasa (56–59)

La Pratique du Soudage (Belgium), 1960, vol. 14, April

Zinc brazing in architecture, J. Liegeois (69–71)

Welded construction of metal framework; Part 2 (72–79)

The functions of the coatings of coated electrodes (80–81)

Przeglad Spawalnictwa (Poland), 1960, vol. 12, No. 7

Standardization in welding in the light of technique development resolutions, Z. Dobrowolski

Joining of metals by means of synthetic resins, R. Brzozowski

Power demand coefficient in shipyard welding installations, R. Kensik

How to qualify welders; Part II, E. Macalik

Schweissen und Schneiden (Germany), 1960, vol. 12, June

Curved railway bridge, A. Ohlemutz (255–258)

Completely welded railway bridge in lattice construction, U. Giehrach (258–261)

Welding fixtures in structural steelwork, A. Coblenz and R. Oswald (262–266)

Application of flame-cutting in ship construction, H. Koops and J. Bentfeldt (267–279)

Schweisstechnik (Berlin), 1960, vol. 10, May

On the fatigue strength of fillet welds, A. Neumann and H. Reinel (170–174)

Identification markings, classification and guarantee of quality of fluxes for submerged arc welding, G. Becker (175–178)

What did the Educational Exhibition for Standardization offer to the welding experts? W. Becker (179–185)

Damage caused by fire due to carelessness during welding operation, F. Lausch (185–186)

South African Institution of Welding Monthly Bulletin, 1960, No. 82, May

Welding in the United States today (6–13)

Welding Design and Fabrication (U.S.A.), 1960, vol. 33, May

Electron beam welding: strong, ductile welds in the active metals (32–33)

How to get better weldments faster, W. R. Edwards (36)

Lighter, stronger frame is fabricated from high-strength steel, J. G. Locklin and F. C. Fleck (38–40)

Continuous fluoroscoping speeds inspection of submerged arc welded line pipe (45)

Highway bridge floor panels are designed for welded fabrication (46–48)

Why vacuum brazing makes better joints, R. F. Gunow (54–55)

Current analyser reduces spot welding set up time, M. A. Ferguson (56–58)

How to weld molybdenum; Part 1, (60, 62–63)

10½ miles of welded steel piping help make ice for skating rink (66–67)

Welding Design and Fabrication (U.S.A.), 1960, vol. 33, June

Production line fabricating and welding a 1,200-ton steel space frame (43–44)

Better fluid lines with brazed fittings, D. F. Collins (45)

Good machine design: saves $1,600 and takes a quarter less space (46)

How to weld molybdenum; Part 2 (50–52)

In-motion X-ray speeds inspection of large tank weldments, W. C. Hitt and D. J. Hagemaier (54–55)

Welded elevator engines are built to take it (56–57)

Automation of spot and seam welding (59–61)

High frequency seam welding is versatile (62–63)

Special flash butt welder joins alloy tool steel to mild steel (65)

Spot welding thin to thick (66–67)

Expendable electrodes are used in spot welding waffle-type honeycomb panels, M. H. Bester (68–69)

RWAA explains hardness testing of resistance welding electrodes, H. A. Mullen (70, 72)

Welding Engineer (U.S.A.), 1960, vol. 45, May

Fundamentals of oxyacetylene welding (38–40)

Better controlled dimensions with magnified template drawings, R. L. Deily (42–43)

Missile optical systems housed in Mig welded aluminium cones (44–45)

Photoelectric control aids weld uniformity, J. Melton (46–47)

Welding speeds building of large space frames (50, 52)

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Zirconium alloy tubes improve reactor design (58)

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Welding Production (U.S.S.R., translated by the B.W.R.A.), 1959, November

Experience in the work of the Central Experimental Welding Shops of VNIIAVTOGEN in the Light of the Decisions of the June Plenum of the Central Committee of the C.P.S.U., A. N. Shashkov

Automatic Submerged-arc Welding of Thin Sheets of Dissimilar Steels, K. V. Lyubavskii and M. I. Sorokina

Automatic Submerged Arc-welding of Commercially Pure Nickel with a Ceramic Flux, K. V. Bagryanskii and others

Adhesive-welded Structures and their Use, V. N. Shavyrin

Characteristics of Austenite Transformation during Fusion Welding, M. Kh. Shorshorov, B. A. Smirnov and V. V. Belov

Measurement of Stresses in Welded Press Frames, P. V. Novichkov

Study of Corrosion Resistance of Aluminium Welds, N. N. Skvortsov

Electro-slag Welding of Turbine Discs from Austenitic and Pearlitic Steels, M. M. Timofeev and E. P. Molchanov

Improved Equipment for CO_2-shielded Arc Welding, I. L. Brinberg, V. N. Suslov, E. Ya. Tselniker and D. A. Grudkin

Using Suspended Seam Welders in manufacturing Motor-car Bodies, A. I. Gulyaev

Mechanization of Work on Assembling and Welding in Producing Road Vehicles, B. I. Avdeev and V. P. Kolesnikov

The Universal Welding Manipulator USM-1200, I. A. Brovko

Welded Acetylene Cylinders, I. I. Strizhevskii and S. P. Kalmanovich

Table Endoscope for Inspection of Welds, L. V. Golub and M. V. Pavlev

Welding Current Remote Control, V. N. Kulikov

Semi-automatic Welding of Body Brackets, A. A. Trigub

New Welding Techniques at the USSR National Economy Achievements Exhibition of 1959, I. A. Brovdo and K. I. Boeva

Automation and Mechanization of Welding Operations in Siberian Enterprises, A. Z. Maikov

Stalingrad Welders discuss the Problems of Development and Use of Progressive Methods Welding, D. N. Ruze and S. V. Yunger

New State Standards on Regulators for the Flame-treatment of Metals, V. V. Bykov and V. A. Korshunova

The Effect of Storage Time on the Hydrogen Content and Mechanical Properties of Arc Welds made with Coated Electrodes

Main Recommendations for Oxygen-cutting of Mild and Low-alloy Steels

Soviet Welding Literature, V. A. Nevskii

Soviet Inventions in Welding

Other Journals

New fusion-welder. Fully-automatic boom-manipulator type machines for North America (*Aircraft Production*, 1960, vol. 22, May, pp. 187–188)

Ultra-high tensile steels. Machining 120-ton alloys. Use of cutting-fluids and carbon-dioxide coolant, L. L. Arundel and R. Kitchingham (*Aircraft Production*, 1960, vol. 22, May, pp. 176–186)

Non-destructive testing of welds, W. M. Wedderburn (*Engineer and Foundryman*, 1960, vol. 25, March, pp. 32–38)

Training in radiography – the present position, H. A. MacColl (*The British Journal of Non-Destructive Testing*, 1960, vol. 2, April, pp. 1–2, 3)

Experimental work on the use of gamma ray scatter for the production of radiographic images, E. E. Baines (*British Journal of Non-Destructive Testing*, 1960, vol. 2, April, pp. 4–8)

The application of irradiation in industry, M. C. Crowley-Milling (*Proceedings of the Institution of Electrical Engineers* 1960, vol. 107, Part A, April, pp. 111–126)

Welding an all-steel boat, H. B. Irvine (*African Oxygen*, 1960, vol. 5, March, pp. 2–3)

Aluminium pipework. An introduction to its use, and methods of manufacture (*Pipes and Pipelines*, 1960, vol. 5, April, pp. 35–38, 44)

Steel pipe manufacture (*Pipes and Pipelines*, 1960, vol. 5, April, pp. 45–52)

Shop fabrication speeds erection of large welded vessels (*Commonwealth Engineer*, (Australia), 1960, vol. 47, 5 March, pp. 50–51)

Fabrication of clad steels, S. Rowden (*Engineering Materials and Design*, 1960, vol. 3, June, pp. 334–338)

Reconstruction of a store, J. N. Turnbull (*New Zealand Engineering*, 1960, vol. 15, 15 March, pp. 101–105)

Electron beam welders (*Engineering*, 1960, vol. 189, 29 April, pp. 588–589)

Ultrasonic welding. Preliminary results in the joining of titanium alloy (*Aircraft Production*, 1960, vol. 22, May, pp. 199–200)

Cast-to-shape tool steels gain favour with industry (*Iron Age* (U.S.A.), 1960, vol. 185, 28 April, pp. 104–110)

ADDITIONS TO THE LIBRARY

BOOKS AND PAMPHLETS

AMERICAN WELDING SOCIETY: Specification C 2.7–59: *Three-year interim report of corrosion tests on metallized coatings* New York, A.W.S.

BRITISH STANDARDS INSTITUTION:
BS.1140:1957. *Spot welding of light assemblies in mild steel.* London, B.S.I. (4*s* 6*d*)
BS.2901: Part 2:1960. *Filler rods and wires for inert-gas arc welding.* London, B.S.I. (Price 7*s* 6*d*)

ELECTRICAL RESEARCH ASSOCIATION: *39th Annual report for the year ended 31st December 1959.* Leatherhead, E.R.A., 1960.

GREAT BRITAIN, Ministry of Labour and National Service: *Annual report of the Chief Inspector on industrial health for the year 1958.* (Cmnd.811) London, H.M.S.O., 1959. (Price 3*s* 6*d*)

HENRY WIGGIN AND COMPANY LIMITED. *Welding, brazing and soldering of Wiggin nickel alloys.* 2nd ed. Birmingham, 1960.

INTERNATIONAL ACETYLENE ASSOCIATION. *Official proceedings of the annual convention for 1957,* Minnesota, 1–3 April, 1957. New York, I.A.A., 1960.

SMITH, A. A. *Notes on pipework design.* Richmond, Association of Engineering and Shipbuilding Draughtsmen, 1959. (Price 3*s* 6*d*)

STANFORD, E. G., and FEARON, J. H., *editors. Progress in non-destructive testing.* Vol. 2. London, Heywood & Co. Ltd., 1960. (Price 55*s*)

WELDING RESEARCH COUNCIL: Bulletin Series 58. *Strength of aluminium alloy 6061-T4 thick walled cylindrical vessels subjected to internal pressures,* J. Marin and Tu-Lung Weng. March 1960, 12 pp.

World list of abbreviations of scientific, technological, and commercial organizations. 2nd ed. London, Leonard Hill (Books) Ltd., 1960. (Price 25*s*)

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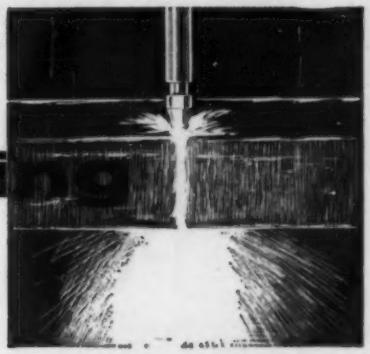

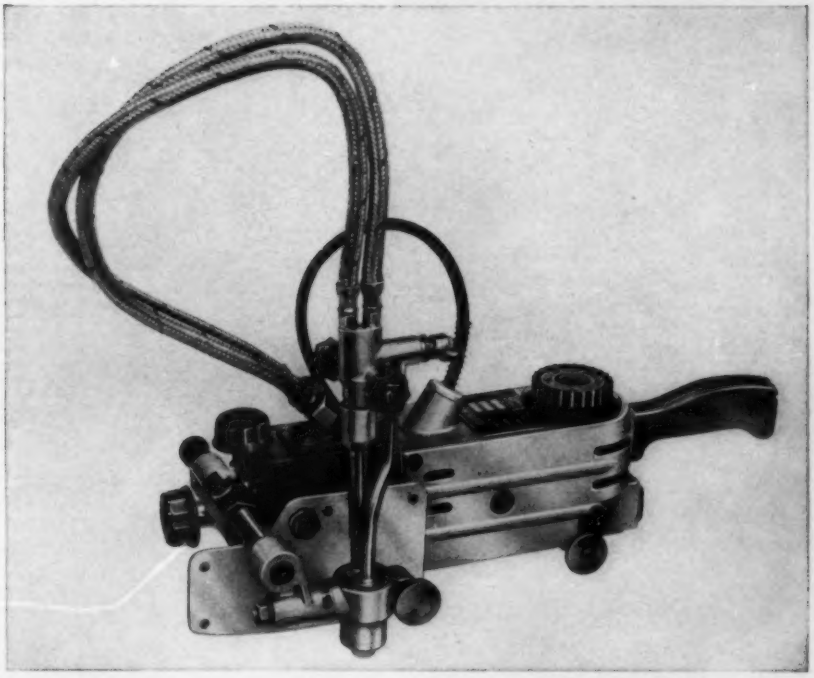

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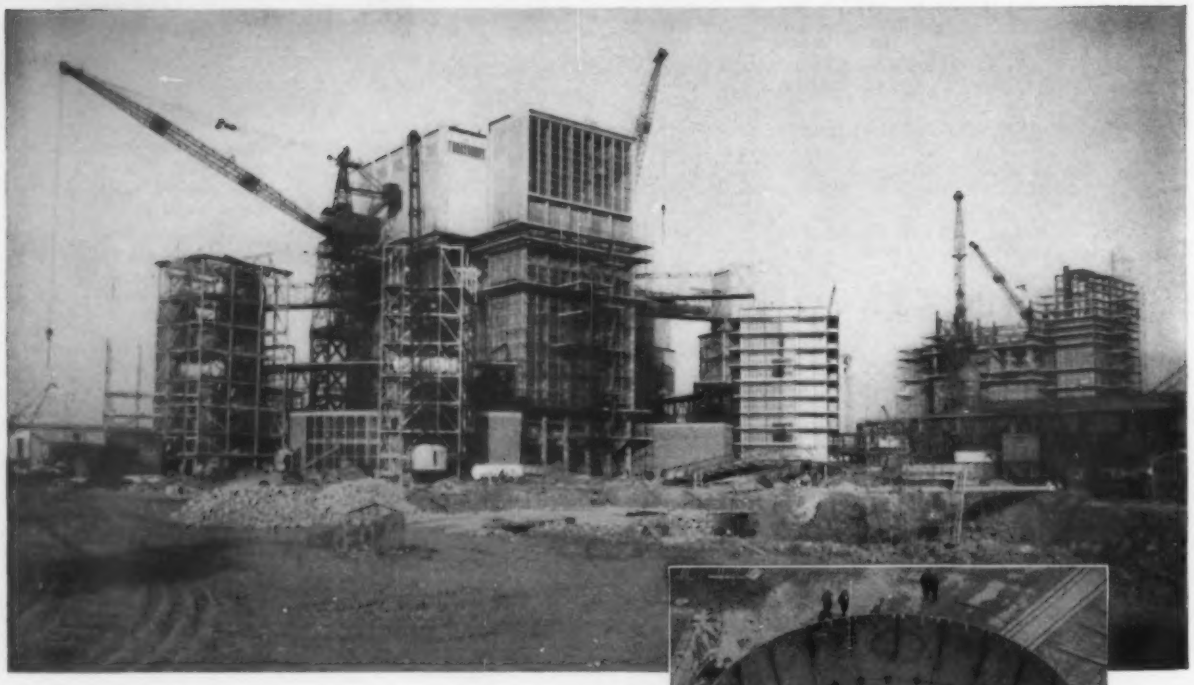

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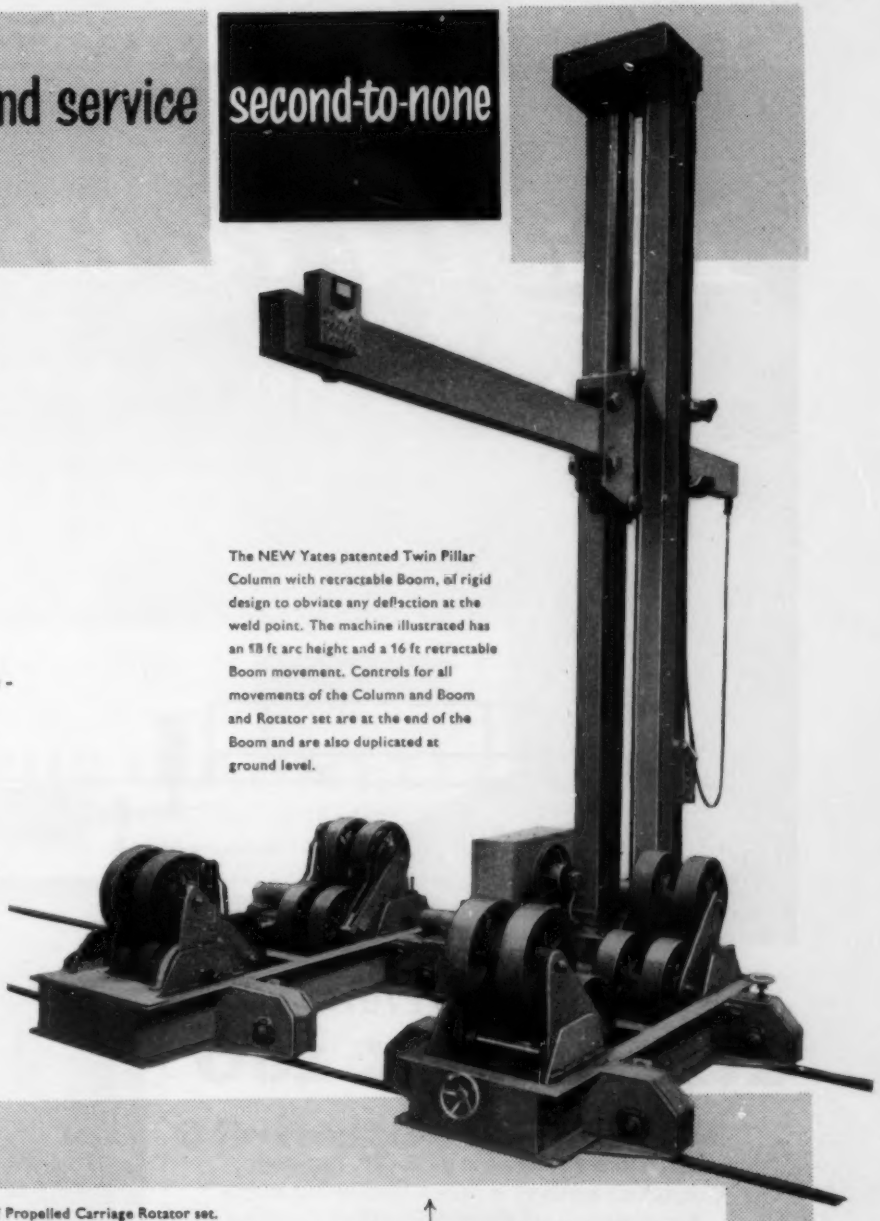

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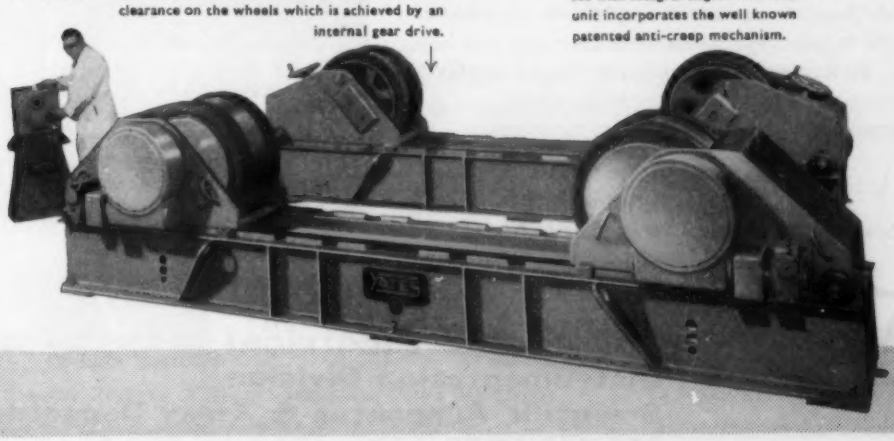

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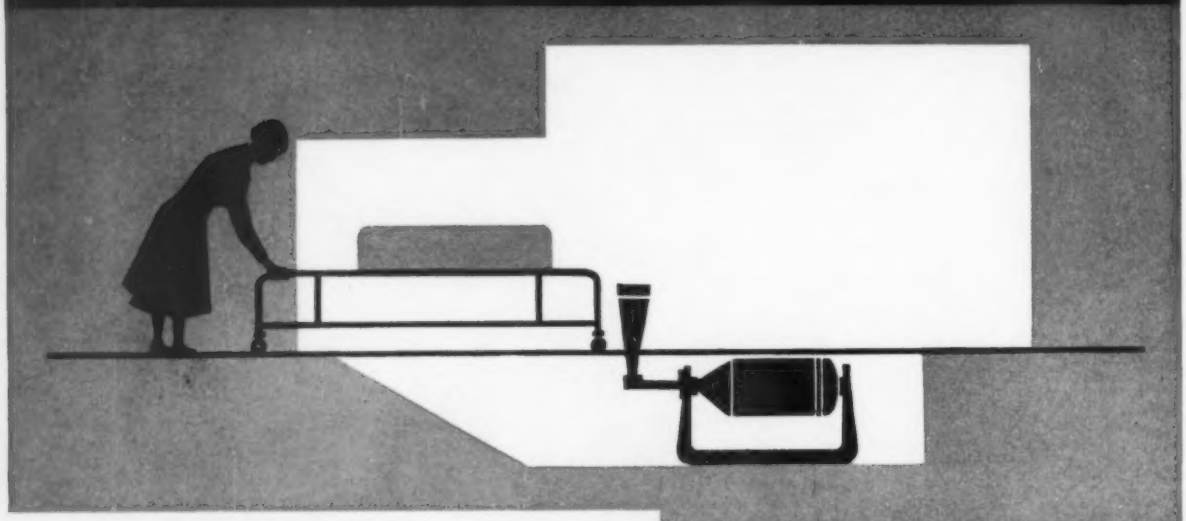

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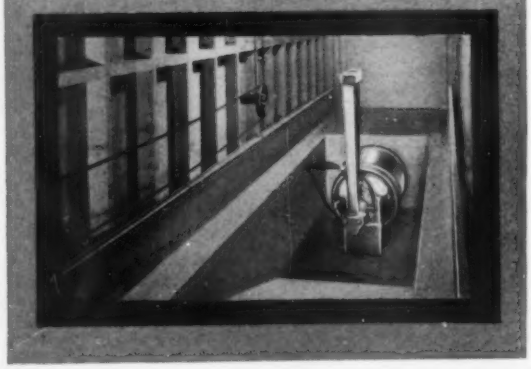

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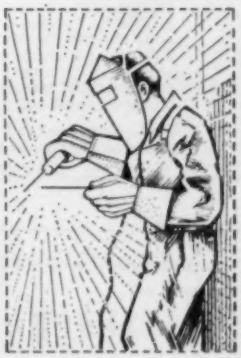

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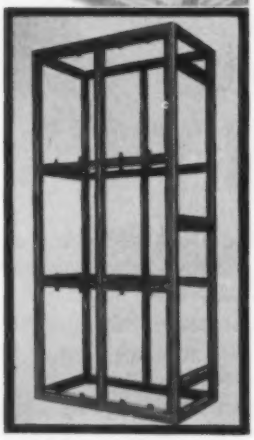

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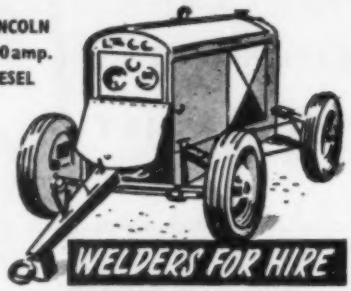

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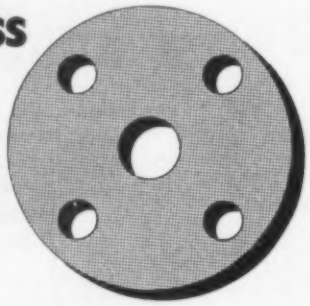

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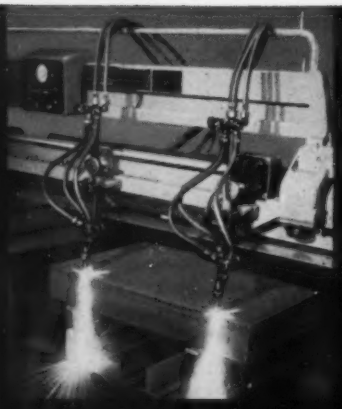

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